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Development of Straw Bale Building in Northern China

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Development of Straw Bale Building in Northern China

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Abstract

This thesis is an investigation of developing suitable types of straw bale building for northern China. Although the technique has been introduced into northern China since 1998, the construction method and potential problems within straw bale walls have not been fully understood and responded.

The research conducted has resulted in recommendations for future straw bale design in northern China based on an inspection of existing buildings. The issues identified with existing construction details were subjected to computational simulation analysis which identified shortcomings in existing practice.

Following the analysis of existing straw bale construction both in north China and worldwide, this thesis proposes modifications to the straw bale construction details currently used in north China. These modifications were incorporated into an experimental building constructed in north China, and after having been monitored for 11 months, the modified construction details were critically assessed of suitability of climatic conditions in northern China. The data demonstrate that rice straw bale walls are resistant to agents of decay in the climate of northern China.

As rice straw is a major raw material for straw bale building in northern China, the water adsorption characteristic of the species of straw is researched in this thesis. Although the surface and cross-sectional structure of the two straw species are different at micro scale, sorption properties of the two straw species are broadly similar. A modified water sorption isothermal model regarding real situations is proposed after understanding of the sorption characteristic of the two straw species. The study on the water sorption property of rice straw and wheat allows for the assessment of durability within a wall construction.

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1. Introduction

1.1. Background

The rapid growth in human population over that last two centuries has had a substantial impact on the global environment. The world population had reached 7.5 billion by 2017 and the total population is expected to surpass 9 billion by the mid-21st century (Bacci, 2017). Fossil fuels (i.e. coal, gas and oil) have been the energy source for human activity since the industrial revolution. The increasing population has led to a greater requirement from the fossil fuels to provide an affordable and abundant energy source (Schipper and Meyers, 1992). The dependency of human activities on the fossil fuels is not expected to change in the 21st century (Schipper and Meyers, 1992).

One significant impact of using the fossil fuels is global climate change. The burning processes of the fossil energy release the Greenhouse Gas (GHG) into the atmosphere (Van der Werf *et al.*, 2009) which are widely considered to be the major reason for global warming caused by human activities. There are six GHGs identified in the Kyoto Protocol: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulphur hexafluoride (SF_6), and two groups of gases, hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs) (Grubb *et al.*, 1997). The Greenhouse gas (GHG) emission is a major cause of global climate change and it has resulted in the warmest 30 years (1983-2012) over the last 1400 years (Pachauri *et al.*, 2014). Global warming has led to glacier retreat, regional climate changes, changes in agricultural productivity, species extinction and many other effects. (Hansen, 1998). As well as the known effects of global warming, there are expected to be further, as yet uncertain, effects in the future. (Hansen, 1998).

To reduce global warming, reductions of anthropogenic sources of GHG have been a priority for many governments. Globally, there are more than 100 countries that have agreed to take responsibility to limit global warming to 2ºC or less compared with pre-industrial revolution levels (Meinshausen *et al.*, 2009). In order to achieve this ambition, international agreements and protocols have been signed to limit the process of global warming and to reduce the GHG emissions caused by human activities. The Kyoto Protocol was one of the first international treaties to commit to reduce GHG emissions. The Kyoto Protocol was adopted in Kyoto, Japan on 11st December 1997 and it came into force in 16th February 2005. The primary objective of the Kyoto Protocol is to control human-emitted GHG levels and different states made individual commitments in the context of differences in their GHG emissions, economy, and potential to reduce GHG (Grubb *et al.*, 1997). The European Union (15 states at the time of the Kyoto negotiations) and a further 38 industrialised countries committed to reduce the GHG emissions to their individual targets on basis of the GHG emissions of 1990 or earlier (Grubb *et al.*, 1997). There are three “flexibility mechanisms” defined in the Kyoto Protocol to meet the emission limitation targets. The mechanisms are the International Emissions Trading (IET), the Clean Development Mechanism (CDM) and the Joint Implementation (JI) (Grubb *et al.*, 1997).

Following the Kyoto Protocol, the Paris Agreement was signed in the Paris, France on the 22nd April 2016. There are three objectives in the agreement:

1. Maintaining a maximum 2ºC increase in global temperature above pre-industrial levels at the end of 21st century and making efforts to limit the increase of temperature to no more than 1.5ºC above pre-industrial levels;

2. Increasing adaption to the impacts of climate change, fostering climate resilience and reducing GHG emissions.

3. Making investments into a pathway towards low-GHG emissions and climate-resilient development (Savaresi, 2016).

There are no mandatory GHG reduction targets or timelines for the nations that have signed up to this agreement. However, the targets of the nations would not be looser than their previously set targets (Savaresi, 2016).

China signed the Kyoto Protocol but there is no target built in the commitment. In 2015 China was one of the signatories of the Paris Agreement. The Chinese government in particular has made a commitment to two specific targets for the reduction of GHG emissions (China.org.cn, 2015):

1. To reduce its GHG emission by 60%-65% as a percentage of gross domestic production (GDP) from a 2005 baseline by 2030.

2. To achieve peak carbon emissions by 2030 at the latest.

Because of booming economic development during last the two decades, China has been experiencing rapid growth of urbanisation. The urbanisation percentage was 46% by 2008 and the urbanisation percentage of China is expected to reach 60% before 2020 (Lin and Liu, 2010). During the urbanisation process, the major energy source is coal (Lin and Liu, 2010). Because of the inevitable increase in energy demand from the urbanisation process, GHG emissions in China will continue to increase significantly until this urbanisation process is completed (Lin and Liu, 2010). Energy consumption and GHG emissions of high-rise buildings is a significant contributor to GHG emissions caused by the urbanisation process in China (Lin and Liu, 2010). The construction industry has been a major obstacle to the achievement of the Chinese target of GHG emission reduction. The current situation of building energy efficiency level is summarised by Amecke *et al.* (2013):

> China's greatest potential for energy savings is in ensuring high energy efficiency standards for new construction. Much of northern China relies on district heating, making it difficult to incentivize conservation using prices. Current lifestyle practices are not energy-intensive, but energy demand is growing rapidly; China seeks to balance low-energy traditions with improvements in comfort and services. Rapid building construction and growth in equipment use means that energy use will continue to increase, and also that potential savings from energy efficiency are large.(Amecke *et al.*, 2013)

To meet the commitment that the Chinese government made in the Paris Agreement, policies adopted by the building industry have been largely defined and supervised by Ministry of Housing and Urban-Rural Development of the People's Republic of China (MOHURD). The majority of policies are realised through statute and industrial standards (Liang and MOHURD, 2014). The strategies of reducing the GHG emissions caused by the building industry focus on increasing the energy efficiency levels of existing buildings and reducing the energy use in newly built buildings. The strategies of increasing energy efficiency levels of existing buildings involve refurbishment of existing buildings and replacing existing building service systems (Liang and MOHURD, 2014). The reduction of energy use in newly built buildings involves higher standards of energy efficiency levels of the buildings, encouragement of prefabricated construction in buildings and promoting the percentage of green buildings in newly built buildings (Liang and MOHURD, 2014). These strategies have been applied as a priority in northern China because of the higher energy reduction potential in the area (Liang and MOHURD, 2014).

1.1.1. Features of climate and energy consumptions of buildings in northern China

The climate in China encompasses a wide range of air temperatures and humidity. MOHURD published the national code for thermal designs of civil buildings which identifies a number of different climatic regions (GB50178-93, 1994). The design and construction of buildings in China is informed by five climate regions differentiated by the climatic characteristics of the regions (Figure1.1). Northern China is in the climatic areas of 'Severe Cold' and 'Cold'. In these two areas, the primary energy consumption of buildings is that of winter heating energy (GB50178-93, 1994).

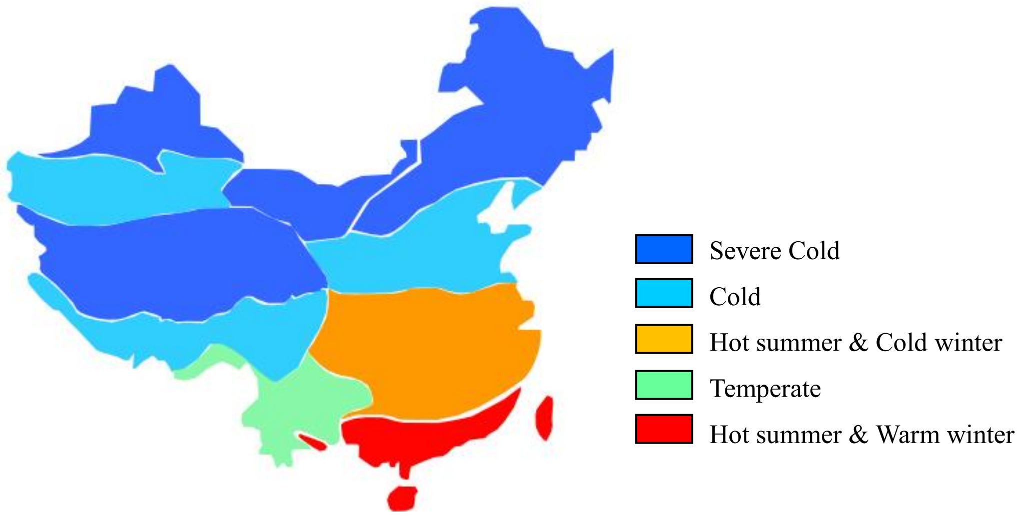


Figure 1.1. Climatic regionalisation in the GB50178-93. (reproduced from. (GB50178-93, 1994)

The need for improvements in building energy efficiency is most critical in northern

China due to the high winter heating demand caused by the regional climatic conditions (Figure 1.2) (Amecke *et al.*, 2013). The Climate Policy Initiative established that floor areas of urban residential buildings had doubled between 2000 and 2008 (Amecke *et al.*, 2013). As a result, the floor areas of residential buildings are expected to contribute up to 90% of total building floor area in China by 2030 (Amecke *et al.*, 2013). Due to the dominating position of domestic buildings, end use energy consumption has a large effect on the total in-use energy of buildings in China. According to the predictions for 2021, compared to the energy consumption level in 1996, the energy use grew at its most rapid rate in China in 2008 (Amecke *et al.*, 2013). Heating energy demand in domestic buildings more than doubled between 1996 and 2008 and became the most crucial factor for energy use of domestic buildings in China.

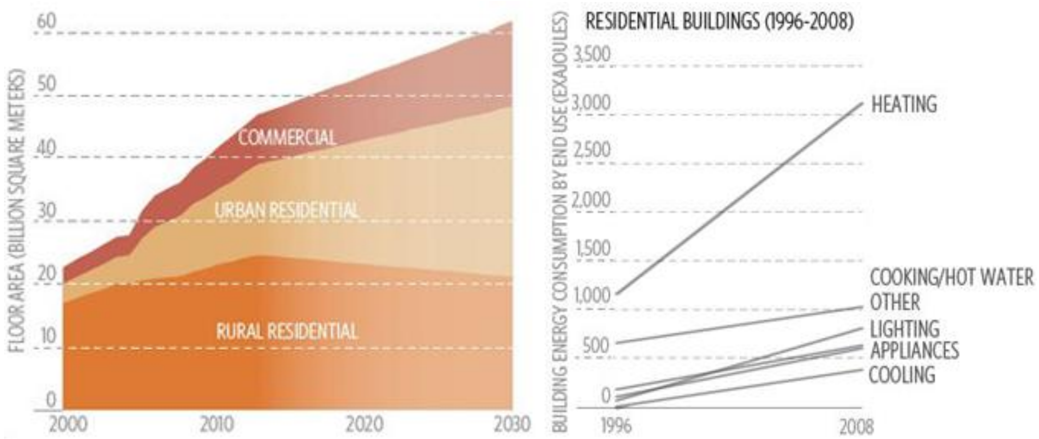


Figure 1.2. Dynamics of floor area of Chinese building stock from 2000-2030 (left) and Chinese building energy use by end use from 1996-2008. (Amecke *et al.*, 2013)

Heating demand is notably high in northern China due to the requirement for thermal comfort in the winter months. In-use energy consumption is the major element of heating energy use during the winter season. As a result, in this region, the proportion of energy consumption associated with heating is much greater than the national average. The latest versions of building regulations commit to a reduction of 50 % on the heating energy consumption of buildings compared with 1980 levels in northern China (JGJ26-2010, 2010; GB50189-2015, 2016). The regulations have been created specifying thermal conductivities of building envelopes, with U-values ranging from 0.25 to 0.7 W/m^{2}K, depending on the height and location of the building in northern China (JGJ26-2010, 2010; GB50189-2015, 2016).

1.1.2. Rationale for straw bale construction in northern China

Straw bale construction uses agricultural co-products in the construction of buildings. It was originally developed in Nebraska in late 19th century, due to shortage of building materials (King, 2006). The straw bale buildings were originally used to make temporary buildings (Figure 1.3). This buildings types were replaced after achieving more industrialised building materials in the Middle West America in early 20th century (King, 2006). The oil crisis of the 1970s helped people to develope ideas of creating more energy efficient buildings. Straw bale buildings were characterised by combinations of low cost, quick construction process and high thermal insulation (Bergeron and Lacinski, 2000). The construction technique was re-introduced in the 1980s in west America and the construction method has become popular worldwide since the oil crisis of the 1970s (Steen *et al.*, 1994).

Figure 1.3. Photo of the Simonton House during construction in Nebraska in 1908. (Bergeron and Lacinski, 2000)

Straw bale construction has now become more recognised globally and has developed into a contemporary building typology and construction method in the western world (King, 2006). The construction technique was initially introduced to northern China by the Adventist Development and Relief Agency (ADRA) in 1998 ((ADRA), 2006b). The project was funded by the ADRA/China, Central Government and Local Governments in northern China and more than 600 straw bale buildings had been finished by 2006 (Gao, 2008). Informed by the practices of the ADRA project, a different design of straw bale building was developed in Jilin province (Cao *et al.*, 2010).

There are four significant advantages to using straw bale construction in the context of conditions in China:

Firstly, Straw bales are a carbon sink building material and it has significant low embodied energy and embodied carbon (Menet and Gruescu, 2012). The carbon in atmospheric CO_2 is sequestered in the body of the plant through the process of photosynthesis (Menet and Gruescu, 2012). Atmospheric CO_2 is converted into plant cells during the growing process, forming the rice and wheat stems. It can be calculated through stoichiometry that 1kg of carbon sequestered in the stem of straw requires the removal of 3.67kg of CO_2 from the atmosphere. This amount of adsorbed carbon will not be released into the atmosphere until the straw bale buildings are demolished (Sodagar *et al.*, 2011).

Secondly, because of the high thermal insulation property of straw bale walls, straw bale houses have low heating energy load and cooling energy load (Bigland-Pritchard, 2005). The U-value of typical prefabricated straw bale panels can reach between 0.11 to 0.19 Wm^2K^{-1} for a 450mm thickness of walling panels (Modcell, 2016). Compared with the thermal performance of the current Chinese standard for walling designs, thermal resistances of the panels are 50% - 300% better than the standard walling construction. Straw bale walls can also provide high quality physical properties including sound insulation, seismic stability of the structure and low fire risk (King, 2006).

Thirdly, the use of straw in building industry will benefit the agricultural economy of northern China. Straw is considered waste material in the farming process of rice and wheat in northern China (Zhang, 2006). Agricultural production in some provinces of northern China consists mainly of rice and wheat. The total annual rice production in northeast China is approximately 203 million metric tons (Grain, 2016). As the production of rice and the production of rice straw is broadly similar, total production of rice straw would be no less than 203 million metric tons. Due to the associated large amount of waste straw, disposal of the material has been an increasing issue for China for decades. Currently, the preferred method of disposal of the straw is for it to be burnt-out in the field (Li *et al.*, 2008). The burning of straw on this scale has become a serious air pollution problem in northern China. This issue demands more environmentally friendly disposal solutions for straw as an alternative to burning in the fields (Li *et al.*, 2008). Air pollution is also exacerbated by the use of coal to heat buildings in Northern China (Florig, 1997; He *et al.*, 2001; Mestl *et al.*, 2007). The high thermal insulation property of straw bale buildings will notably decrease heating demand and therefore less coal will be used for winter heating in northern China.

Fourthly, use of straw in building construction also reduces pollution and carbon emissions by avoiding the need to burn the straw. As there is little existing research which quantifies the burnt straw in northern China, the quantity of reduction of pollution and of carbon emission remain uncertain. However, in view of the large rice production and limited recycling scheme operated for rice straw in the area (Li *et al.*, 2008), widespread use of straw by the construction industry would certainly result in a significant reduction of pollution and of carbon emissions. It also provides added value to farmers by commercializing a waste product in context of agricultural economy in northern China. Using straw in the Chinese construction industry could therefore resolve the straw disposal problem and simultaneously decrease consumption of coal for heating because of its high thermal resistance. Furthermore, using straw as a construction material can sequester large amounts of atmospheric CO_2 through photosynthesis during its growing phase. Because of the high thermal resistance of straw bale walls and the carbon sequestration of straw, large scale use of straw bales by the construction industry could help to deliver the Chinese government's 2030 carbon reduction target. These features of straw bale construction offer a sustainable approach to the reduction in the environmental impact of the construction industry in northern China.

1.2. Research aims and objectives

1.2.1. Overarching aim

The aim of this research project is to propose appropriate building designs for straw bale buildings which optimise their durability given the known sensitivity to degradation of existing straw bale buildings in northern China. Because little research has been conducted on the use of rice straw in straw bale buildings, there is also the need to characterise rice straw and rice straw bales in term of durability and hygrothermal performance.

1.2.2. Specific objectives

The specific objectives of this research are:

- The first objective is to understand the durability of the straw as a building material. The objective involves achieving both an understanding of moisture adsorption process of rice straw and an evaluation of the susceptibility to degradation of both wheat straw and rice straw in high humidity and high temperature conditions. Whereas wheat straw has been heavily researched, there is little published research on rice straw. For this reason, this study places particular emphasis on rice straw and on the characterisation of the microscopic structure and moisture adsorption properties of both rice straw and wheat straw.. Having obtained an understanding of the two straw species, a modified isothermal model of straw will be proposed in the context of the actual environmental conditions that straw bale buildings are subjected to in northern China

- Secondly, this research will provide an understanding of the performance and condition of existing straw bale buildings in northern China. It has been almost 20 years since the initial introduction of straw bale buildings by ADRA in 1998. There is much research focusing on the benefits of straw bale buildings and on the feasibility of implementing straw bale building based on the ADRA project in northern China. However, there is little research evaluating the buildings in terms of buildability and possible performance and durability issues. This research will investigate both the straw bale buildings from the ADRA project and other straw bale buildings where innovative designs were informed by ADRA project. The research will involve site visits to straw bale buildings, evaluation of construction methods, description and analysis of defects found in the existing buildings and recording the opinions of straw bale buildings by local residents.

- The third objective is to evaluate the durability of straw bales in straw bale buildings in the climatic conditions in northern China. An experimental building in the area will be constructed to allow the evaluation of the durability of straw bale buildings when exposed to the climatic conditions of northern China. Long-term monitoring research of the straw bale walls of the experimental building will be conducted and the results of the monitoring research will be analysed by applying existing models for predicting straw degradation. The suitability of the models will be examined through a forensic investigation of the experimental building at the end of the monitoring research period.

1.2.3. Contribution to knowledge

The contribution of the thesis to knowledge can be summarised as follows:

- Understanding the moisture adsorption properties of rice straw;
- Understanding the impact of the microscopic structure of both wheat straw and rice straw on the water adsorption characteristics of each straw species;
- Proposing a modified sorption isothermal model of rice straw and wheat straw in the context of actual environmental conditions ;
- Justification of susceptibility to degradation of straw in high temperature and high humidity environment inside straw bale walls;
- Understanding of the disadvantages of existing straw bale buildings in northern China and the reasons behind the disadvantages;
- Long term monitoring results of hygrothermal performance of straw bale walls in the climatic area of northern China;
- Understanding the susceptibility to degradation of rice straw in the climatic conditions of northern China;
- Evaluating the suitability of existing models for predicting straw degradation.

1.3. Scope of the research

The scope of the research is focused in the main on the environmental conditions typical of northern China since the objective of this thesis is to develop a design for straw bale buildings that is appropriate for that location.

Since rice and wheat straw are the raw materials readily available for straw bale construction in northern China, it is only the properties of these two straw species which are studied in this thesis.

When considering the potential challenges for straw bale buildings in northern China, it is the potential for bio-degradation that is the major concern for this building typology. To understand these risks, it is the hygrothermal environment induced by the climate found in northern China inside the straw bale walls which is the focus of this research. Because northern China is such a vast area, the study is limited to conditions occurring in Changchun in Jilin Province which can be considered to be representative of the typical climatic characteristics of northern China. The study of long term performance of a single straw bale building is made on an experimental building constructed for that purpose in Changchun in Jilin Province.

1.4. Structure of the thesis

Chapter 1 presents the background and the objectives of the research.

Chapter 2 initially reviews the existing understanding of straw bale construction and existing research on straw bale construction. This chapter examines the potential difficulties for the developing straw bale buildings in northern China as follow. As the durability of straw is the major consideration for this type of building, the mechanisms involved in straw degradation and models for predicting straw degradation are also discussed.

In the Chapter 3, the methodology and approach of the research are explained. There are three research approaches applied; one for each of the three different research objectives: Laboratory experiments are mostly applied in understanding the straw as a building material; Site visits are conducted to examine existing straw bale building in northern China; Construction of experimental building and subsequent monitoring research are used to understand the susceptibility to degradation of straw bale construction in the climatic conditions of northern China.

The Chapter 4 presents the research results from the laboratory experiments. The isothermal research discusses the water adsorption properties of both rice straw and wheat straw. Susceptibility to degradations of rice straw and wheat straw are also examined in high temperature and high humidity environments.

Results of evaluations of existing straw bale buildings in northern China are described in the Chapter 5. The evaluations examine both the condition of the existing straw bale buildings through on-site visits and the construction detailing implicated in deterioration of their condition. Feedback from the local residents of the buildings is also included in this chapter.

Chapter 6 initially describes the construction of the experimental building. Results of long-term monitoring research are discussed as follows. By applying the existing models for predicting straw degradation into the monitoring results, the susceptibility to degradation of straw bales is examined. To verify the predicted susceptibility to degradation of straw bales inside the experimental building, two on-site visits to the experimental building were conducted. The initial winter visit identified the construction quality of the building and the second on-site visit involved opening up of the walling section of the experimental building and visually checking of the condition of the straw inside the walls.

Chapter 7 bring all the results presented in the Chapter 4, Chapter 5 and Chapter 6 into analysis. The first part of this chapter analyses the suitability of the existing building physics models and proposes modifications to improve their reliability.

This chapter also compares the construction technique of the existing local straw bale building with ones practiced elsewhere worldwide. Defects identified in the ADRA project through on-site visits are analysed through computational simulation following an analysis of the feedback of local residents. The monitoring data from the experimental building are analysed by considering the local climate of the building site, stacking methods of bales and detailing designs of the experimental building. The final section of this chapter brings all the analysis together to propose appropriate designs for straw bale buildings in northern China.

Chapter 8 is the conclusion of the thesis and brings together the whole research and makes recommendations for developing straw bale buildings in northern China.

The diagrammatic representation of the work flow through of the thesis is shown in Figure 1.4.

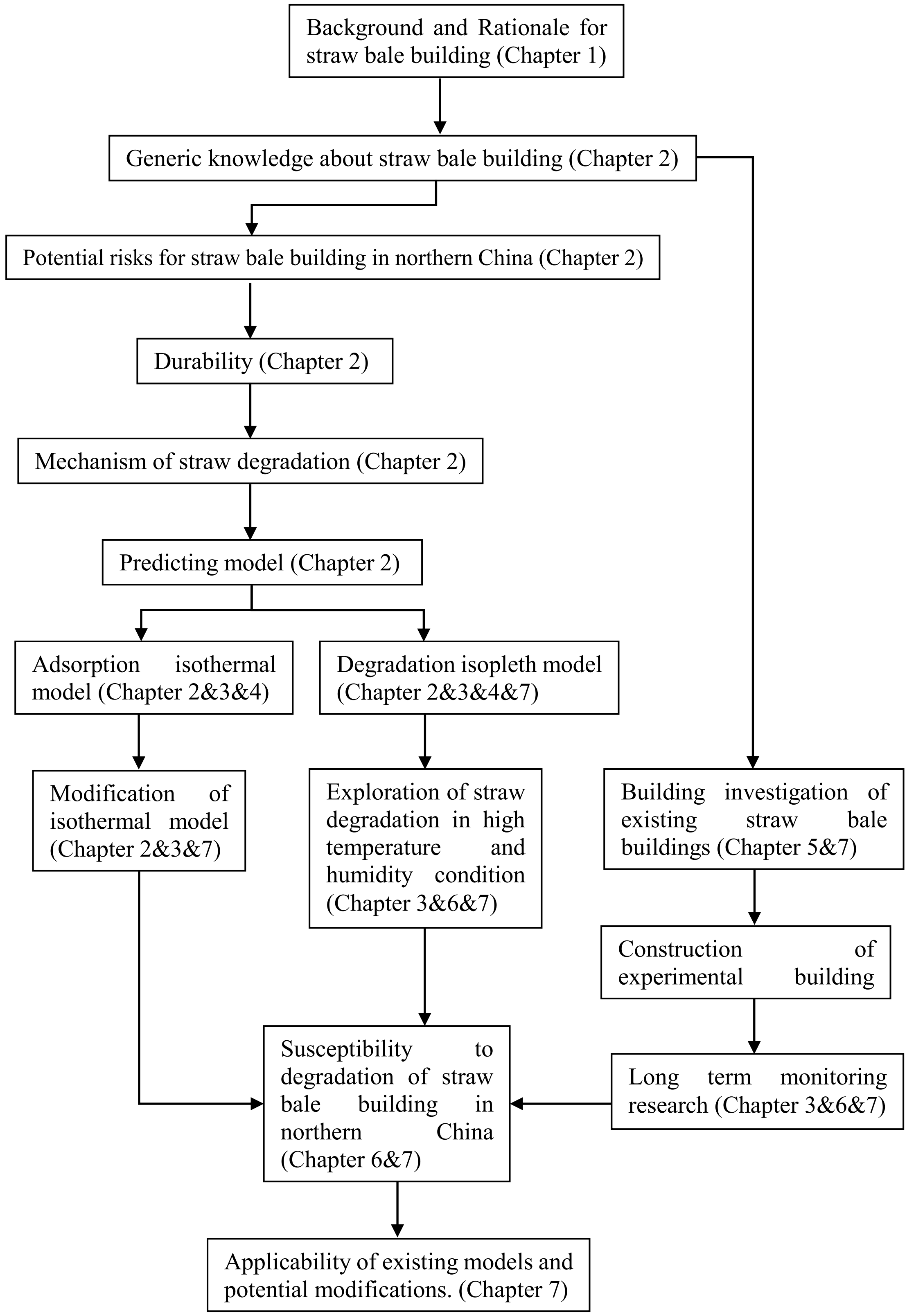


Figure 1.4. Work flow through the thesis.

2. Literature review

This chapter provides an overview of the state of the art of straw bale construction worldwide. This gives context for the potential benefits and risks of using straw bale construction in northern China. Among the potential risks identified, susceptibility to degradation of straw is particularly discussed due to concerns of bio-based building materials as discussed below. The mechanisms of straw degradation are explained and discussed in this section following a review of the methods currently employed for predicting straw degradation in the context of the different degradation mechanisms found in straw.

2.1. The state of the art of straw bale construction

This section initially reviews the straw bale as a building material and the development of building techniques employed for straw bale buildings. The following sections discusses elements involved in the conventional straw bale walling construction following prefabricated straw walling constructions which are innovated from the conventional ones.

2.1.1. Straw as a building material

In the process of cereal agriculture, the purpose of cultivate activities are to produce grains such as rice, wheat and corn. Therefore the other parts of the crop are by-products in the cultivate activities. The dried stalks which are known as straw are the above-ground part of the cereal plants and are removed after harvest of the grains (Staniforth, 1979). Straw is around one meter long after harvest of grains. Traditionally, straw was used for fuel, animal bedding, fibre reinforcement of earth constructions and supplement of animal diet worldwide (Bronsema, 2010). However, due to limited use of straw in the modern industry in northern China, the straw is considered a waste material of agricultural activities (Wu *et al.*, 2013).

Some of the provinces in the northern China contribute large share of agricultural productions in China. Wheat, rice and corn are major grain crop in the area. There are three major provinces contribute 56% of total wheat production in China in 2014 (Figure 2.1). Rice is not typically grown in the regions due to the availability of water. However, there is a rapid growth of rice production in north China (Peng *et al.*, 2009). The rice growth areas have expanded in northeast China and some regions in Henan province and Shandong province (Figure 2.2). The large volumes of rice and wheat production in China are associated with extremely large volumes of waste straw. It is certain that straw as a building material is available in substantial volumes in the regions (Maclean *et al.*, 2013).

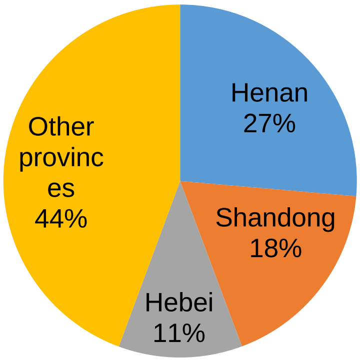


Figure 2.1. Separation of Wheat production of China in 2014. (Statista, 2015)

Figure 2.2. Area of rice growing regions in China in 2014 (1 dot = 10,000 ha) (Maclean *et al.*, 2013)

The significant benefit of using straw bales in building industry can also be attributed to the low environment impact at the disposal stage of the building materials. The straw is used in the natural state in the straw-based building materials. The biodegradable feature of straw will cause much less pollution issues than mineral based building materials (Lawrence, 2015).

2.1.2. Typical straw bales for construction

The straw bales for construction are produced from the mechanical baling machines in harvesting process of grains (e.g. rice and wheat). The mechanical balers pick up loose straw on-field and form the loose straw into either block shape straw bales or large round straw bales (Jones, 2009). The block shape bales can be directly used in construction of straw bale buildings; however, the round bales need re-bailing to achieve a cuboid shape (King, 2006).

The typical straw bale used for building is shown in Figure 2.3. For mechanical baling machines, the baling processes of straw press loose straw into sections of straw which are known as flakes. The thicknesses of the flakes are generally around 100mm. One typical straw bale is consisted of several flakes along the axis of length. Dimensions of typical bales are 350mm (height) X 450mm (width) X 900mm (length). The width and height of the bales are decided by the dimensions of balers and the variations of the dimensions are not significant between different bales. Because the lengths of straw are generally longer than the width of straw bales, the straw is curved in each flake. The combination of the curved flakes gives straw bales a ‘cut end’ and a ‘folded end’ along the two faces of straw bales. The cut end of bales consists of cutting edge of straw stems in the straw. Due to variation of straw length in the straw bales, the folded end features different lengths of loss straw on the side. The different two ends can be easily identified in straw bales (Figure 2.4).

Due to different applications of straw bales in the straw bale constructions, the densities of the bales vary between 80kg/m^3 to 120kg/m^3 (King, 2006). Density of a typical load-bearing straw bale is more than 110kg/m^3. For the non-load-bearing straw bales, lower densities of straw bales (80kg/m^3-100kg/m^3) can be applied in the straw bale buildings (Goodhew *et al.*, 2010).

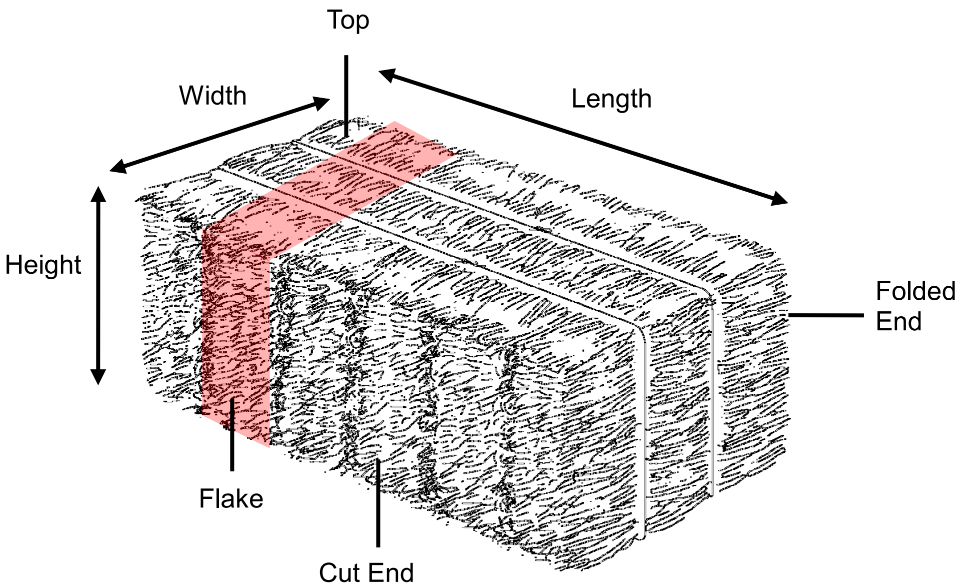


Figure 2.3. Nomenclature of basic bales for construction. (Concluded from (Myhrman, 1998; Bergeron and Lacinski, 2000; Jones, 2009)

Figure 2.4. Cut end (right) and folded end (left) of rice straw bales in straw bales.

Straw bales can be stacked flat or on edge in the straw bale walls. The flat stacked bales have the cut end and folded end on the wall surface. The laid flat bale walls are best used for structural purposes and the cut end and folded end will produce strong bond between plaster and bales (Jones, 2009). Alternatively, bales can also stacked on-edge in the straw bale walls. In the on-edge stacking method, the long length of straw and baling wire are exposed to the wall surface. Due to smooth outer surface of straw, the laid on-edge bale walls have weaker bond with plaster than the laid flat walls (Jones, 2009).

One potential benefit of the laid on-edge stacking is the lower thermal conductivities of the walling construction than the laid flat bale walls. As straw is mostly baled in a certain direction within straw bales, bales can be identified as two orientations which are perpendicular and parallel to the straw orientation (Figure 2.5). The laid flat bales are perpendicular to heat flow direction of walling construction, whereas heat flow of walls is parallel to the bales laid on-edge.

Figure 2.5. Straw orientations (red arrows) in bales.

Different stacking methods was first investigated by McCabe in 1993. The specimens are wheat straw bales with an average density of 133kg/m^3 (McCabe, 1993). In the research, the measured λ Value is 0.046 W/mK when heat flow is parallel to straw orientation and 0.061 W/mK when heat flow is perpendicular to straw orientation (McCabe, 1993). Following McCabe's work, FASBA, known as the association of straw-bale construction of Germany, conducted a series of experiments to understand the connection of thermal conductivity of straw and the orientation of heat flow (Strohballenbau, 2009). In the experiment various lengths of straws are examined by applying heat flows which are perpendicular to straw orientation and parallel to orientation (Strohballenbau, 2009). The experiments use the guarded hot plate method to examine every individual specimen with different straw lengths (Strohballenbau, 2009). Compared to placing straw to heat flow in parallel, placing them perpendicularly can achieve better thermal resistance (Strohballenbau, 2009) and total thermal conductivity reduction of perpendicular placing can reach more than 50% parallel placing (Strohballenbau, 2009). The laboratory results show that thinner straw bale wall with laid on-edge bales can achieve similar U-value as the laid flat bales. However, this feature may not significant in real constructions. The results of the FASBA are based on straw stalk rather than bales in the research of McCabe (1993). Due to relative randomness of straw orientation within straw bales, the significance of straw orientations on thermal conductivity in the research of McCabe (1993) is not as obvious as the ones in the research of FASBA. The insignificant effects of straw orientations are also be confirmed in the industry (Jones, 2009).

2.1.3. Conventional straw bale wall construction

The very first straw bale building was a school house and it was built in Sand Hills, Nebraska in 1896 or 1897 (Kay *et al.*, 1990). The initial straw bale buildings were constructed for shelters and they were abandoned when there are other building types available in the area (Bergeron and Lacinski, 2000). Due to lack of maintenances of the buildings, there were only 9 surviving straw bale buildings in the region of Sand Hills as of 1990 (Kay *et al.*, 1990). There are two types of structure of conventional straw bale walling:

The original straw bale walls are designed to bear the weight of roofing in Nebraska (King, 2006). The walling type of straw bale construction also contain historical precedent of the development of straw bale buildings (Steen, 2000).This Nebraska style straw bale buildings have load-bearing straw bale walls which are featured simple to build and cost-effective for self-builders with limited skills in construction (Jones, 2009). Other benefits of the “Nebraska Style” is the ethical for raising buildings in the absence of structural systems (Jones, 2009).

The weight of the roof construction can also be taken by a separate frame structure (typically timber) in straw bale walling constructions which is known as the in-fill or non-load-bearing straw bale walling constriction (King, 2006). Because of the separate structure systems in the in-fill straw bale walls, the type of straw bale walling is considered to consume more material than the load-bearing straw bale walls. However, the load-bearing walls used more timber than in-fill walls in two identical straw bale buildings in Arizona for intensive requirement of timber to keep stability of the straw bales in walls (Steen *et al.*, 1994). One significant benefit of the in-fill straw bale walls is the construction process of the straw bale walls. The structural frames and roofing constructions can be constructed prior to levelling the straw bales which provides higher levels of protections for straw bales from raining during construction (King, 2006).

Both of the two types of straw bale walls have similar components and constructions of the straw bale walls. The components are reviewed as follow:

a. Foundation

In consideration of issues of rising damp, the straw bales are not directly placed on the concrete slab or the foundations of the straw bale buildings. There is a toe-up construction that connects straw bales and foundation to prevent damp damage from ground (Bergeron and Lacinski, 2000). The construction elevates the straw bale walls off the surface of the concrete slab or the foundations of the straw bale buildings (Bergeron and Lacinski, 2000; Jones, 2009). There are three typical toe-up designs which are shown in Figure 2.6. Toe-up constructions have a vapour barrier layer to prevent damp damage from ground and allow moisture within the straw bale walls to drain away (Bergeron and Lacinski, 2000). The toe-up construction ensures that straw bale walls are kept away from ground water damage on slabs during construction and it provides protection against any potential leaks of water (Bergeron and Lacinski, 2000). The Toe-up system is widely used worldwide (Bergeron and Lacinski, 2000).

A development of the typical toe-up construction is the base-plate construction of straw bale walls (Jones, 2013). The base-plate incorporates the typical timber toe-up construction and hazel pins for fixing first layer of straw bale walls (Figure 2.7). Thermal Insulation materials are installed in the space between the outer edge of timber and inner edge of timber (Jones, 2013). Comparing to the conventional toe-up constructions, the base-plate toe-up construction integrates the pinning studs and the toe up constructions. Comparing to the conventional toe-up constructions, the integration provides better connections between pinning studs and the toe up constructions and therefore results in more solid bound between straw bales and the toe-up construction.

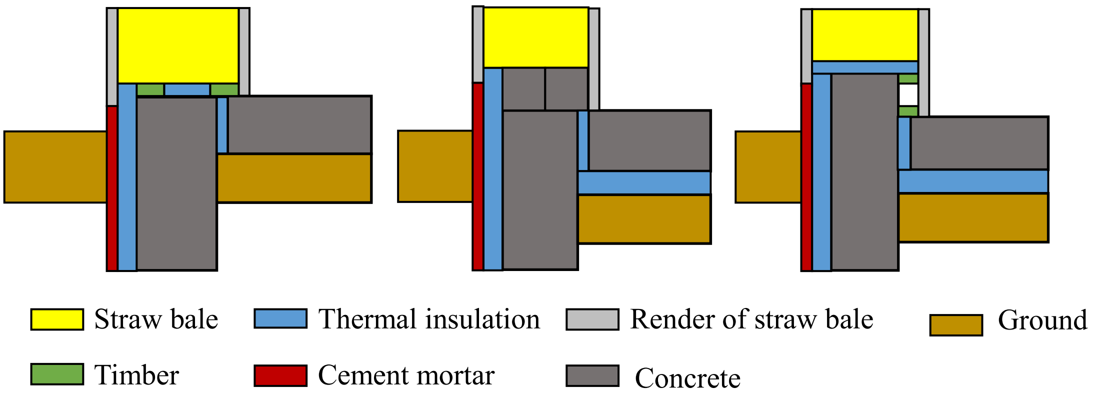


Figure 2.6. Typical toe-up (left), toe-up with blocks (middle) and toe-up with knee wall (right). (Bergeron and Lacinski, 2000)

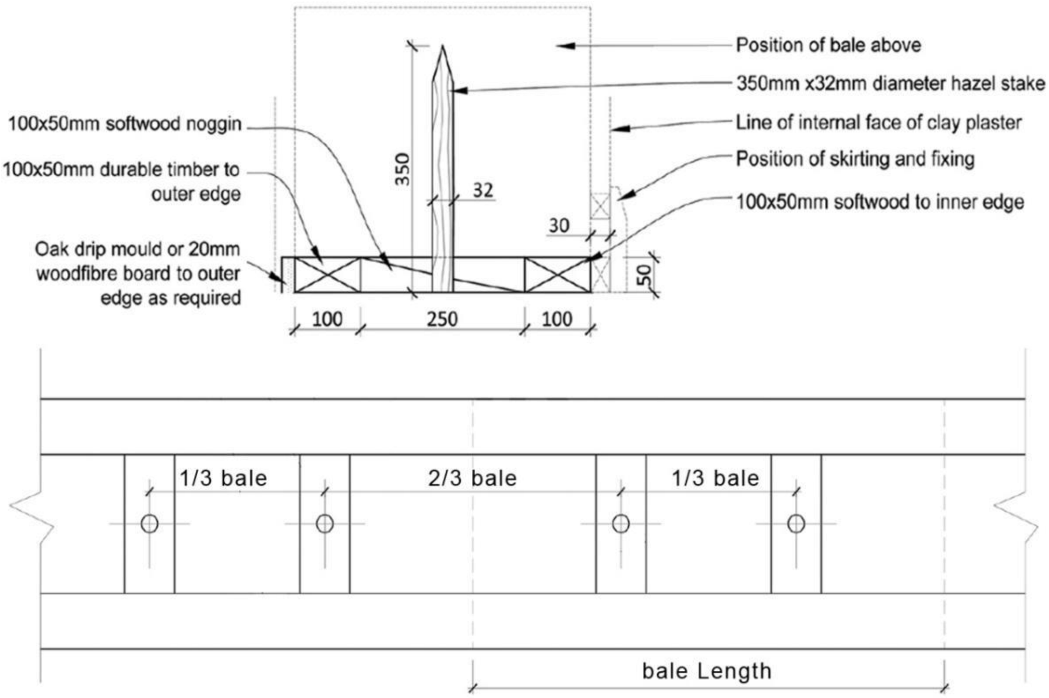


Figure 2.7. Base plate design. (Jones, 2013)

The different toe up constructions may not have significant impact on the straw bale walling constructions in practice in northern China. Due to low winter temperature in the local area, the toe-up constructions should be sufficiently insulated to minimise frost issues on the interface of straw bales and the foundations (Li, 2012). As a result, the timber toe-up with insulation layers may be less problematic than the conventional concrete toe-up constructions.

b. Pinning system

Pins are incorporated in the straw bale wall systems to provide structural stability between bales in both load-bearing structure of straw bale walls and in-fill structure of straw bale walls (Myhrman, 1998). Although the effect of pins is not accounted for in the structural design of in-fill straw bale construction (Bergeron and Lacinski, 2000), the elements are still essential for the practicality of bale stacking of the walls (Jones, 2009). There are different forms of pins in current practice. Rebar staples and all-thread steel rod with pointed end are used in the loading bearing straw bale construction in USA (Figure 2.8). The pinning system of the in-fill straw bale walls is similar to the one in the load-bearing walls.

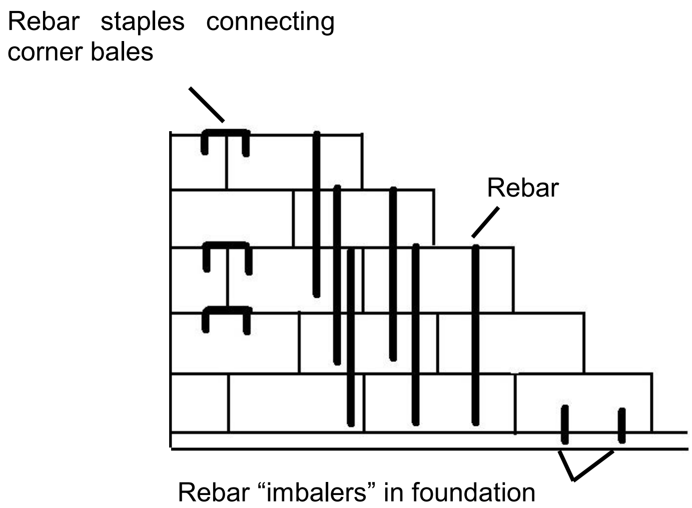


Figure 2.8. Pinning system for loading bearing straw bale walls with 3 tie bales laid flat. (Myhrman, 1998).

The system is simplified by using natural shaped hazel studs to replace the rebar studs and the rebar staples (Jones, 2009). The irregular shapes of hazel studs provide similar effects of the all-thread steel rod (Figure 2.9). Because of the wide availability of the raw material, the modification is considered to be a cost efficient and environmentally friendly solution (Jones, 2009). To achieve better integrity of straw bale walls, bales are tied up at corners of first layer of the walls in the hazel pin system (Jones, 2009). However, due to the weakness of the ties, this tie-up construction cannot be accounted in structural calculation (Jones, 2009).

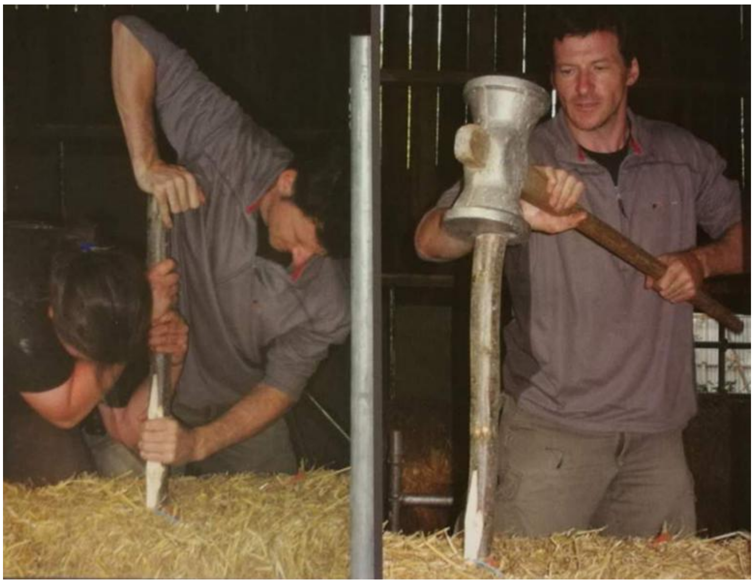


Figure 2.9. Hazel stud pines of straw bale wall system (Jones, 2009).

Considering the low availability of hazel in northern China, the rebar pins may be suitable for the straw bale constructions in the area. However, in comparison with the hazel pins, the high price and low workability of steel rebar may limit the use of the pinning system in the industry. Alternatively, the hazel pins can be replaced by timber stud in northern China. The fast-growing poplars are widely available in northern China (Lang *et al.*, 2012) and it can be used as the pinning studs in the pinning systems of straw bale constructions. There is no practice of the poplar pins in the straw bale buildings in northern China and therefore the effects of the timber stud is remain uncertain.

c. Selecting finishes

The finishes of straw bale walls have to serve three purposes: Protecting straw bales from weathering, form structural stability of the straw bale walls and maintaining breathability and drying trend of straw bales. There are three typical rendering materials which are cement, lime and clay that can be used for straw bale constructions. Gypsum is a conventional surface finishing material, however, due to poor weathering resistance of gypsum, it is recomended only to be used on the inner surface of straw bale walls (Myhrman, 1998). The rendering constructions are normally reinforced with the addition of chopped fibre materials (e.g. straw, glass fibre and etc.) or metal mesh to increase overall strength of the rendering constructions (Jones, 2009).

Uses of straw bale walls may be problematic in northern China for selecting appropriate rendering materials. The climate of the north is dry and cold in winter and hot and humid in summer in China. The weathering condition may require the rendering construction both weathering resistance and high breathability. Cement based rendering is widely used in northern China for its weather resistance of the material. However the rendering construction may lead to degradation of straw bales for its low breathability in northern China during summer. Due to breathability and good eventual hardness of the lime based rendering, it may be appropriate for the straw bale constructions. Lime-based renderings were widely used in buildings before cement was introduced in China and its proven weather resistance in the climate conditions in northern China (Liu, 2015). However, it is not certain that the builders in the industry are familiar with the rendering material in northern at present.

In addition, the load-bearing straw bale buildings may be problematic for selecting appropriate rendering materials. In the load-bearing constructions, the rendering material is the key to ensure lateral stability and to carry the weight of snow in winter for the straw bale constructions and therefore the cement based rendering construction serves the purpose. However, the cement rendering has low breathability and it may lead to straw degradation in the straw bale walls in the climate of northern China. As a result, the load-bearing construction may not be appropriate in northern China for difficulties to find appropriate rendering constructions.

2.1.4. Modern straw bale construction (PSBC) of walls

Prefabricated Straw Bale Construction (PSBC) is a prefabricated construction technique to utilise straw bale in buildings (Wall *et al.*, 2012). This building technique combines the conventional straw bales and the superiority of controlled prefabricated construction method (Wall *et al.*, 2012). Compared with conventional straw bale construction, the main benefit of PSBC is that the construction method minimises the risks associated with wet weather on the construction site (Wall *et al.*, 2012). The prefabrication processes of the PSBC are completed in local factories and the processes ensures that the straw is not exposed to rainfall (Wall *et al.*, 2012). The benefits also involve better quality control of PSBC compared with onsite construction of straw bale walls (Wall *et al.*, 2012). Further benefits of PSBC include the reduction in onsite construction duration, no waste removal and lower risks of fire on construction site due to elimination of loose straw (Wall *et al.*, 2012).

a. PSBC panels of ModCell

ModCell was one of the first companies to produce PSBC. The PSBC are in the form of PSBC panels and the panels are typically consisted of engineered timber frames, in-fill straw bales and lime render (Maskell *et al.*, 2015). The dimensions of the engineered frames are typically 100mm X 480mm to accommodate the dimensions of the infill straw bales. The size of the panels vary largely in different buildings projects and are typically 3.0m (width) X 3.2m (height) (Figure 2.10). The infill straw bales are stacked to form walls and they are pre-compressed during the process to increase stability and reduce thermal bridging due to gaps between bales and frames (Shea *et al.*, 2013). The sizes of the panels can vary depending on different projects. The bales are finished without mesh with 30mm lime render which is the least thickness of lime render possible without the use of a rain screen in the climatic environment in UK (Lawrence *et al.*, 2009c).

The in-fill straw bales in the PSBC panels are different from the straw bales in conventional straw bales construction methods. Unlike the two different sides of the straw bales used in conventional straw bale construction, the in-fill bales are cut to a uniform width to eliminate the folded side in the PSBC of the ModCell panels (Modcell, 2016). The folded sides of the straw bales are cut off in the ModCell products and the dimensions of the bales are reduced to 420mm (width) X 350mm (height) X 900mm (length). This treatment eliminates the effects of having two different surfaces when the straw bales are assembled and leads to an easier assembly process in building the PSBC panels. However, the effects of the treatment are not fully examined on the hygrothermal environment within straw bales in the PSBC panels.

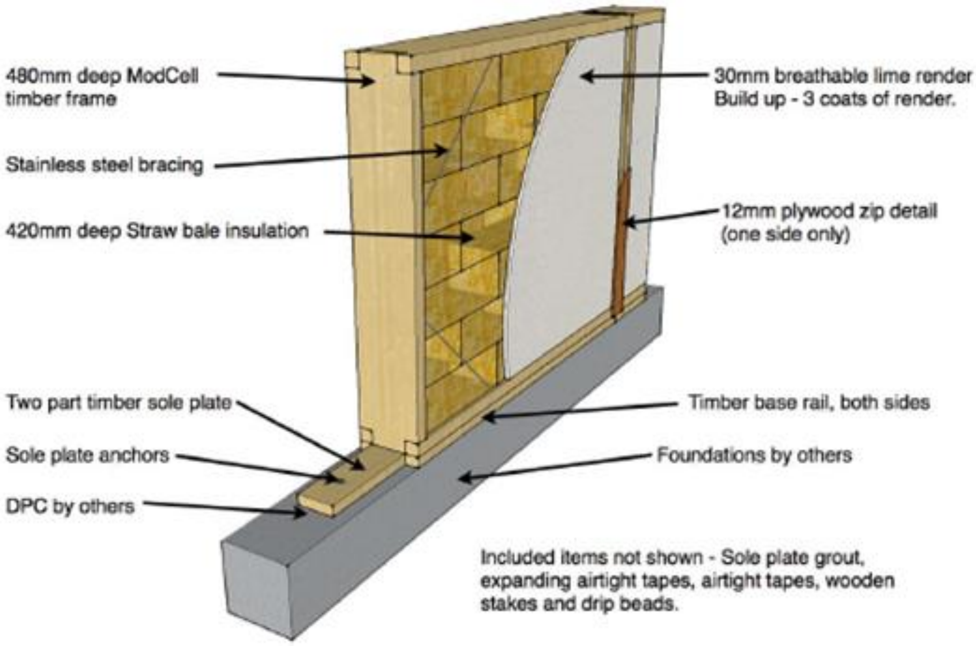


Figure 2.10. Prefabricated Straw Bale Construction (PSBC) of ModCell panels. (Modcell, 2016)

The ModCell panels have been used in a large number of projects. One of the more high profile applications of the ModCell product was the construction of the Low Impact Living Affordable Community (LILAC) project in Leeds. This project includes a 20 household community in Bramley, west Leeds on an former school site (Chatterton, 2013). The PSBC panels of the ModCell products are used to form the walling of the domestic buildings in the LILAC project (Figure 2.11). The project features of low energy consumption of residential buildings Chatterton, 2013). According to energy consumption data from International (2014), the energy use of the LILAC can be separated as follow: Average 35.73 kW/m^2 for space heating, average 39.22 kW/m^2 for hot tap water and 30.00 kW/m^2 for lighting (International, 2014). Comparison between the energy demand of the LILAC project and other benchmarks show that the energy consumption level of LILAC project is far better than CIBSE Guide F benchmark and it is close to PassivHaus standard (Figure 2.12).

Figure 2.11. Low Impact Living Affordable Community (LILAC) in Leeds. (Modcell, 2013)

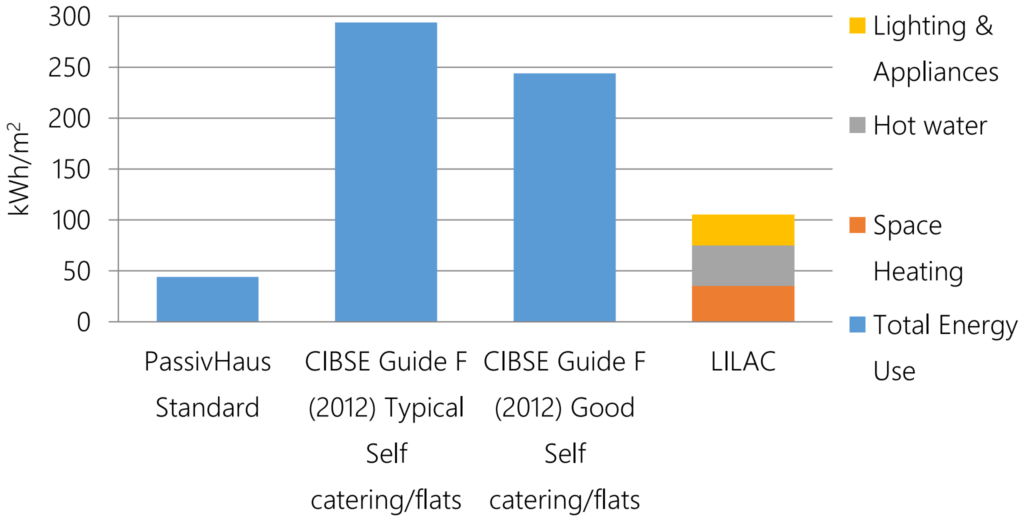


Figure 2.12. Comparison of LILAC and other benchmarks (Data of benchmarks from (Clark, 2013))

b. PSBC panels of NatureBuilt

Another PSBC system, from a Canadian company NatureBuilt Walls provides panellised straw bale walls (Figure 2.13). The principles of the PSBC of the products supplied by NatureBuilt are similar to the ModCell. The frames of the PSBC panels of NatureBuilt walls are timber and the in-fill straw is in the form of bales. The material of rending layer and plastering layer is different from the ModCell products. Cement based rendering layer is applied in the products of NatureBuilt Walls (Magwood, 2012). The frames of the PSBC panels of NatureBuilt Walls are different from the frames of the Modcell. Unlike the one piece of timber plate applied in the Modcell, the timber studs are applied in the PSBC of the Naturebuilt. The timber frame of the PSBC of Naturebuilt may cause cavities and hollows between adjacent PSBC panels. However, due to the PSBC of the products of the NatureBuilt Walls have only been applied in a single project in Canada and there is no industrialised manufacturing process of the PSBC products applied in other projects (Magwood, 2012), the effects of the timber stud frames on thermal resistance of walls remain uncertain.

Figure 2.13 Prefabricated Straw Bale Construction (PSBC) of the panels of NatureBuilt Walls (Magwood, 2012).

c. Prefabricated Straw Construction (PSC) of Ecococon

Apart from the PSBC developed by the Modcell and the NatureBuilt, another prefabrication method of using straw is developed by Ecococon in Lithuania. The Prefarication system of Ecococon consists of in-fill straw, timber frames and a plastering and rendering layer. The assemblies of the PSBC walls requires only simple tools and standard screws during the erection process of Ecococon walls (Ecococon, 2016). The prefabrication panels of the Ecococon use in-fill loose straw rather than the straw bales (Figure 2.14). Straw stems are stacked in several layers in the timber frames and they are compressed at the same time during the stacking process (Ecococon, 2016). According to the statement of the Ecococon, this stacking method of straw can effectively reduce the gaps between straw and result in high uniformed density of in-fill bale walls (Ecococon, 2016).

Figure 2.14. Prefabricated Straw Bale Construction (PSBC) of panels of Ecocon. (Ecococon, 2016)

Comparing to the in-fill bales in the Modcell and the NatureBuilt, the key difference of the prefabricated straw panels of Ecococon is the stacking method of straw. In the prefabricated panels of Modcell and the NatureBuilt, the in-fill process of straw is similar to conventional in-fill straw bale walls. There are cavities and hollows between bales which are sealed by loose straw after pre-compression process of the bale walls (Jones, 2009). Due to difficulties in finding internal hallows between bales in walls, qualities of straw bales walls are largely depending on the experienced builders (Jones, 2009). Although the problem is not significant in the PSBC walling panels, similar problems can be identified in the Modcell products (Figure 2.15). There are identifiable liner thermal bridging between different bales and between bales and timber frames in Figure 2.15 which indicate hollows and cavities within the straw bale walls. However, due to there is little scientific research to compare the differences of the in-filled loose straw and the in-filled straw bales and the benefits of the stacking method of in-fill loose straw remain uncertain in the Ecococon products.

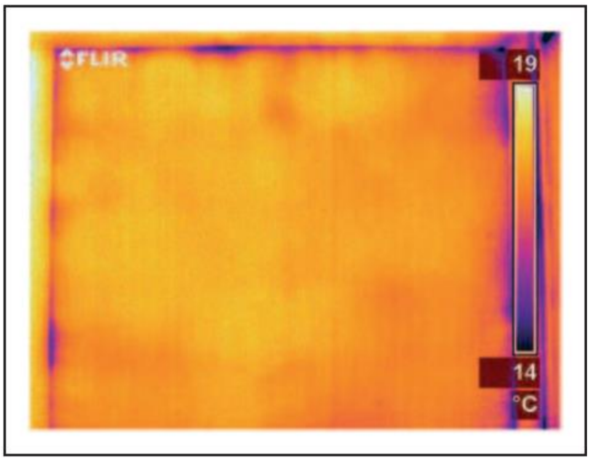


Figure 2.15. Thermal image of panels of the Modcell product. (Shea *et al.*, 2013)

While both the Modcell and Ecococon systems use timber frames. The timber frame of the Ecococon products are made of timbers which have a sectional dimension of 45mm X 95mm (Figure 2.16). The lengths of the timbers vary according to the requirements of the PSC panels. Compared with the engineered timber frames of ModCell products, the timber frames of the Ecococon products show less potential thermal bridging issues. Because of the use of timbers in constructing the timber frames of the Ecococon products, the linear thermal bridges are not as significant as the PSBC panels of the ModCell Products.

The design of the in-fill method of straw and the design of timber frames gives the PSC panels of Ecococon products high thermal resistance. Typical U-values for the ModCell panels is 0.190 W/m^{2}K (Shea *et al.*, 2013). The thermal resistance of the straw panels of Ecococon products is 0,056 W/mK with a resulting overall U-value of 0.107 W/m^{2}K (Ecococon, 2016). The panels are certified PassiveHaus building material to meet the PassiveHaus requirement (Ecococon, 2016).

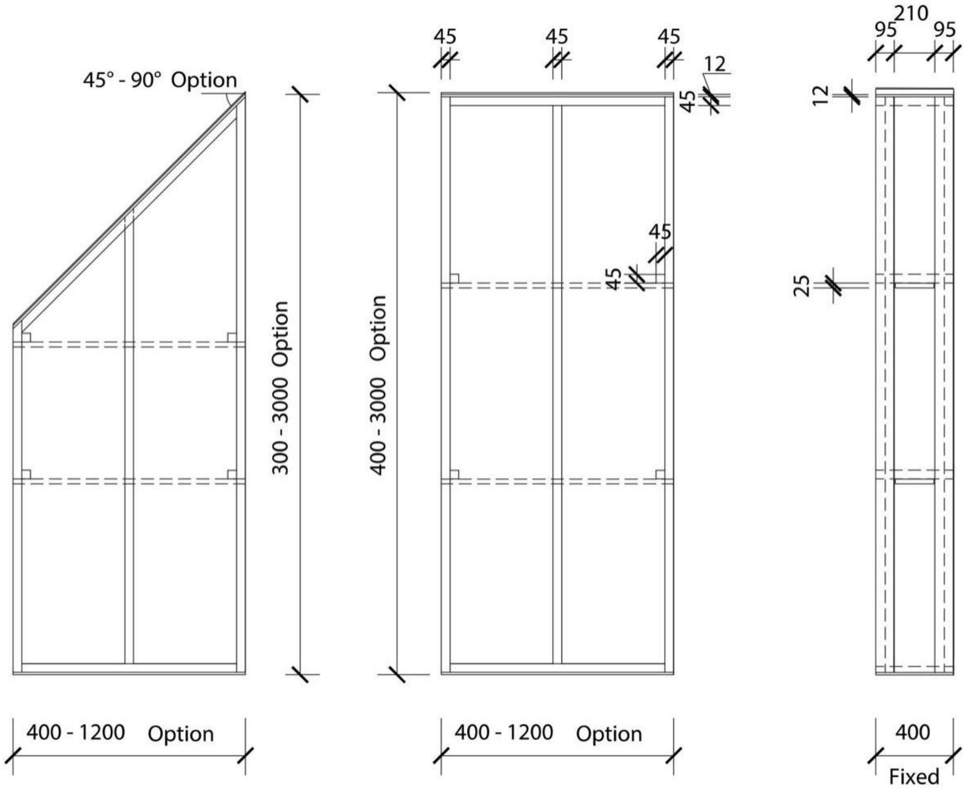


Figure 2.16. Timber frames of the PSBC panels of the Ecococon products. (Ecococon, 2016)

External rendering layer assembly is unique in the PSC panels of the Ecococon products. A layer of Wood fibre boards is installed on external surface of in-fill straw for protecting straw in the walling panels from long-term high humidity environment and for increasing walling unit thermal insulation (Ecococon, 2016). The thickness of the wood fibre boards ranges from 60mm to 100mm. The wood fibre board increase the thermal resistance of the walling assembly to meet the Passive House standard (Ecococon, 2016).

2.1.5. Existing straw bale buildings in northern China

The first straw bale buildings in China were constructed at the turn on in 1998 by the Adventist Development and Relief Agency (ADRA), central government and local government (Figure 2.17). By the end of the project in 2006 the total number of straw bale buildings was in excess of 600 and many of these buildings are still occupied by local residents ((ADRA), 2006b). The straw bale buildings were used for housing and for community centres in rural areas in northern China (Zhang, 2006). For training purpose, the ADRA organised and printed an unpublished training manual before work of construction. In the manual, standard construction details and construction methods are illustrated ((ADRA), 2006b). Following the completion of the straw bale buildings in Jiamusi in Heilongjiang province, technical standards were developed by Department of Construction of Heilongjiang Province (DCHP) and became a collection of technical drawings in 2006.

Figure 2.17 One typical straw bale house in the ADRA project in northern China. ((ADRA), 2006b)

The straw bale buildings of the ADRA project has been reviewed focusing on their buildability, energy efficiency levels and fire safety of the straw bale walls. The construction of straw bales as a facade material of farm house in rural area is established to cost less than typical brick façade ones (Zhang, 2006). The cost for brick façade in rural China is approximately ¥400/m^2 (~£44). Compared the construction cost of brick facade to a straw bale façade which is estimated to be ¥300/m^2 (~£33), the straw bale walls are estimated 75% of the construction cost of the brick walls in northern China (Zhang, 2006). There are two main factors contributing to this fact: Firstly, due to limited use of straw in northern China, straw is a kind of waste material in China. Using straw bale as a building material in China is a utilization agricultural waste and therefore there is ignorable cost of purchasing straw in China (Zhang, 2006). Besides, due of simpler construction techniques than masonry brick farmhouses are involved in the straw bale construction, lower expenditure on workmanship can be achieved (Zhang, 2006). Comparing to the construction process of brick walls, construction of straw bale walls involve less builder onsite and faster construction process (Zhang, 2006). The energy saving potentials of the straw bale buildings are also analysed on the basis of the ADRA project (Wang and Zhang, 2005). Comparison of heating demand of the straw bale buildings and the typical farmhouses shows that the energy demand of straw bale buildings are lower than 40% of ones of the local farmhouses in northern China (Wang and Zhang, 2005). Higher energy efficiency levels of the straw bale buildings have been achieved with lower room temperature in warmer areas in northern China (Wang and Zhang, 2005). Fire resistances of the walling construction of the ADRA project was analysed by the National Institute of Fire Research of China in 2011 (Wang *et al.*, 2011). A duplicated straw bale wall from the ADRA project was examined under the national standard for fire resistance (GB/T 9978.8-2008) (Wang and Zhang, 2005). The results show that the duration of fire resistance of straw bale walls are no less than 3 hours under the standard conditions of the GB/T 9978.8-2008 (Wang and Zhang, 2005). Low oxygen levels inside straw bale walls stop fire penetrating through the walling construction and the high thermal insulating properties of the straw bales limit the temperature raise on the unfired surface of the straw bale wall (Wang and Zhang, 2005).

Other than the research on the ADRA project, researches also focus on applicability of straw bale buildings in northern China and modifying the straw bale construction by applying other structural frames. Liu *et al.* (2012) investigated the application of straw bale construction of a demonstration project in farm houses in Ningxia province. The research compares internal temperature of straw bale farm houses and conventional brick farm houses. The results of the comparisons show greater thermal comfort of straw bale walls than conventional brick walls. Li (2012) studied on the applicability of straw bale constructions in northwest rural farm houses. In the research, current residential statuses including climate features of residential buildings and their energy consumption are examined. Applicability of straw bale construction is discussed in consideration of raw material supply, workmanship and labour cost, thermal performance and sustainability. The results show a potential widespread utilisation of straw bale construction in northwest of rural China. After completion of the ADRA project, few straw bale buildings have been constructed in China. The existing straw bale buildings are mainly in the form of a brick-concrete frame infill straw bale construction. Following the ADRA project, a research project organised by Jilin Jianzhu University developed a steel frame straw bale house in 2010. Construction methods and joint designs are illustrated in a research paper in 2010 (Cao *et al.*, 2010). The modifications on the structural frames feature lower building cost and shorter construction schedule than the brick frame straw bale buildings (Cao *et al.*, 2010). The project is reviewed with respect to their construction methods and the detail designs in the following chapters.

2.2. Potential risks of using straw bale buildings in northern China

Assessments of the risks of applying straw bale buildings are essential before developing the building type in northern China. There are three major concerns of the straw bale buildings in northern China: Firstly, the structural safety of straw bale buildings is a leading issue for the building type in northern China. The following concern for applying straw bale buildings in northern China is the regulations and the standards approving the building type. Thirdly, the durability and degradation potentials of the material is also a crucial consideration for using straw bale buildings in northern China. Each risks of the issues will be discussed in this section following solutions of the issues.

2.2.1. Regulation

The need for building regulations of straw bale buildings increases with the number of straw bale building after 1980s in the US. The first permitted straw bale building referred to the international building permit and was awarded in 1989 in New York State in US (Goodhew *et al.*, 2010). There are two existing standards specifically for supporting straw bale constructions. The first one is adopted by the local government of Tucson/Pima County in Arizona in US in 1996. There are mainly four considerations involved in the standard: Allowable dimensions of walls, standard connections between bales and other building elements, mechanical properties and standard tests of straw bales (Swan *et al.*, 2011). Following the initial regulations, a more recent version of local straw bale standards was developed in California in 2002 (King, 2006). Dimensions of walls, connections with other building components and mechanical properties are standardised in the regulations. The standards can sufficiently support building straw bale constructions in the regions.

There is no approved standard for straw bale construction other than in the USA. Even though construction codes for straw bale buildings are not available in most of current practice in other countries, properties of straw bale constructions are referenced from scientific research. The constructions will be examined individually by inspectors from building control and the buildings are able to pass the standard for health and safety, fire resistance and energy efficiency (Goodhew *et al.*, 2010; Jones, 2009).

The situation in China is quite similar to the situation in UK. There is also no current specified construction code for straw bale construction in China. However, the construction can be complied with other regulations for general use of building materials. By applying the non-loading-bearing straw bale walls, the regulations for structural safeties of buildings would not be an issue for straw bale buildings. Fire safety of straw bale walls is a leading concerns of the public. The research of fire resistance of the straw bale walls of the ADRA project have shown that straw bale walls can pass the fire safety regulation of non-load-bearing building materials (GB/T 9978.8-2008) (Wang *et al.*, 2011).

There is no direct reference to the planning policy for the straw bale buildings in northern China and it would be a major issue for permission of the straw bale buildings in northern China. However, with increasing focusing on reducing energy demand and carbon emission in building industry, the planning policies for straw bale buildings would have positive trend in the next few years. The commitments of carbon reduction targets of the Chinese government require both long-term reduction of energy demand of buildings and the embodied energy used in the constructions (Zhang and Wang, 2016).

In consideration of embodied CO_2 of buildings in northern China, the embodied carbon of building materials contributes the largest amount of GHG in China (Figure 2.19). GHG emission from construction are generated by three major activities (Hong *et al.*, 2015): Building material production and transportation (95%); On- and off-site human activities (4%); and Construction equipment and transportation (1%). A study of carbon emission of building materials of 78 office building shows that bricks and insulation material contribute 4.81% and 1.18% of total carbon emission in office buildings respectively (Luo *et al.*, 2016). Because straw bale walling system commonly replaces bricks and insulation in buildings, using straw bale walling systems will make a contribution to the reduction of construction GHG emission of between 3%-6% depending on different cases (Zhang and Wang, 2016; Luo *et al.*, 2016; Su and Zhang, 2016).

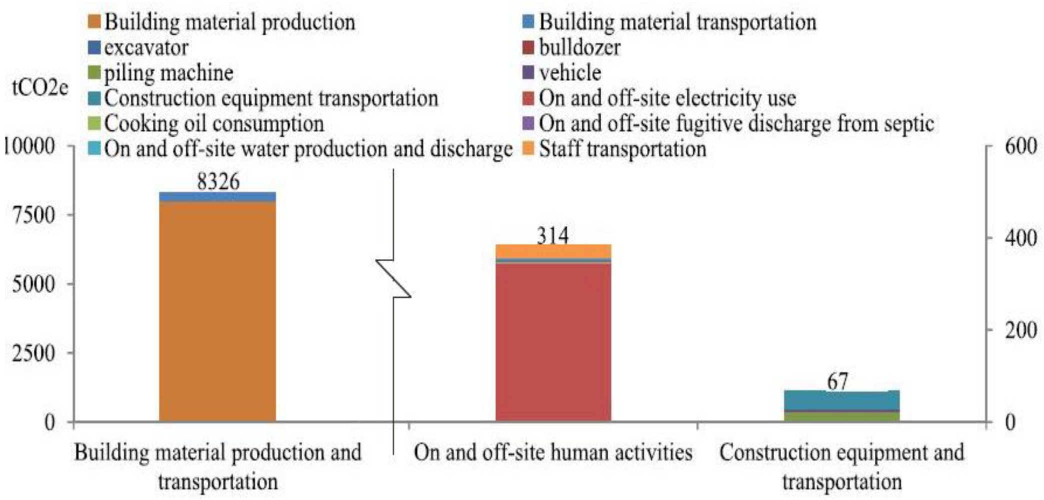


Figure 2.18. GHG emission of reference construction activities in China.(Hong *et al.*, 2015)

2.2.2. Structural safety

The major considerations for structures of straw bale walling systems are similar to those for normal wall constructions. Straw bale walling systems should be able to withstand gravity, in-plane loads and out-of-plane loads (King, 2006). The gravity and in-plane loads are not major concerns of the in-fill straw bale walls which use a separate structural system. Structural stability of straw bale walling systems need to be evaluated in supporting imposed loads from intermediate floors, roof and self-weight, resistance to earthquake and stability under wind loads. The compressive resistance of straw bales shows a large variation, depending on both the species of straw and the packing density of the bales(King, 2006).

Straw bales can also be subject to continuous deformation under increasing compression loads (Walker, 2004; Bou-Ali, 1993). However, rigid render materials with a good connection with the straw bales can significantly improve structural properties of the system (Walker, 2004; Jones, 2009; Adedeji, 2011; King, 2006). In the light of these findings, straw bale walling systems should always consist of a combination of straw bales and a render layer for structural purposes. Wind load represents the most commonly occurring out of plane load imposed on walling. The wind pressure has an effect on whole buildings rather than surfaces of well supported walls. Previous research into existing straw bale buildings has demonstrated that wind load is not a critical factor for straw bale walling systems(King, 2006).

The ability of straw bale walls to resist compression loads is a function of the way in which the walls are constructed. The construction elements within a straw bale walling system can produce a variation of bearing capacity of straw bale walls from 19.2KN/m with 170mm deformation to 66 kN/m with 55mm deformation (Figure 2.18). These capacities are also significantly affected by the render construction and orientation of bale placements (Vardy and MacDougall, 2006). Research shows that laid flat bale walls are 36% stronger than laid on-edge walls (Vardy and MacDougall, 2006). Doubling the thickness of the render layer on both sides can increase the strength of bale walls can be increased by 65%. The minimum thickness of a render layer on the construction should not be less than 12.7mm when applied to laid on-edge straw bale walls (Vardy and MacDougall, 2006).

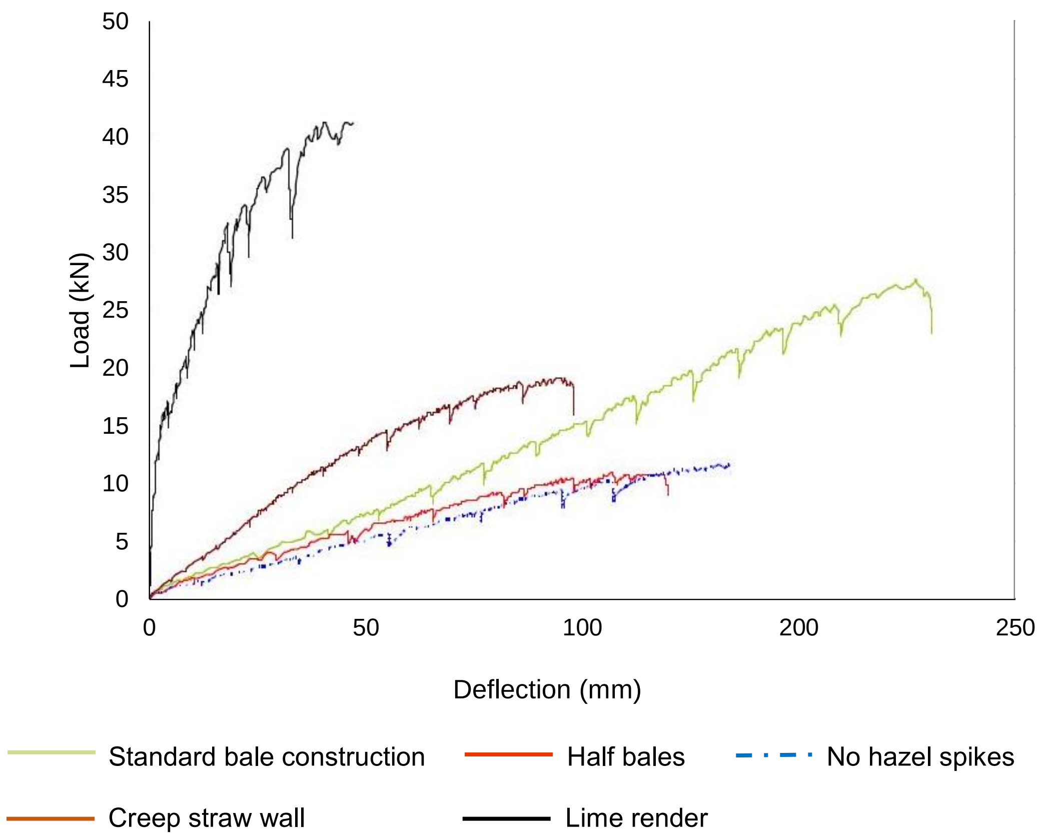


Figure 2.19. Experimental result of vertical deflection of 6 layer flat laid straw bale walls. (Walker, 2004)

In-plane loads on straw bale walls have been extensively studied and the research has been reviewed (Aschheim *et al.*, 2014). Research on allowable shear to straw bale walls are shown in Table 2.1 in which the units are converted from inch and lbf/ft to mm and KN/m respectively. There are several conclusions can be drawn from the research:

- Mesh in the render layer will greatly increase ability of resistance to shear force of straw bale construction;
- Types of mesh can make great difference and greater stiffness of mesh can make straw bale walls more resistant of shear force;
- There is not a great difference in lateral force resistance between lime rendered straw bale walls and cement-lime rendered straw bale walls;
- Thickness of render layer contributes little influence to the resistance of shear force.

Table 2.1. Allowable share for plastered straw-bale walls. (reproduced from (Aschheim *et al.*, 2014)

Wall Designation	Render material	Plaster thickness (both side)	Mesh	Allowable shear (kN/m)
A1	Clay	38 mm	None	0.88
A2	Clay	38 mm	2 by 2 high-density polypropylene	2.00
A3	Clay	38 mm	2 by 2 by 14 gauge mesh	2.77
B	Soil-cement	25.4 mm	2 by 2 by 14 gauge mesh	7.73
C1	Lime	22.2 mm	17 gauge mesh woven wire	4.81
C2	Lime	22.2 mm	2 by 2 by 14 gauge mesh	6.57
D1	Cement-Lime	22.2 mm	17 gauge mesh woven wire	5.54
D2	Cement-Lime	22.2 mm	2 by 2 by 14 gauge mesh	7.59
E1	Cement	22.2 mm	2 by 2 by 14 gauge mesh	7.88
E2	Cement	38 mm	2 by 2 by 14 gauge mesh	9.92

Current practice of straw bale buildings is all brick-concrete in-fill construction in China. However, the load-bearing system could also be constructed in the regions. Straw bale wall construction is not covered by current standards in China. The major concern addressed by the standards is the structural safety of the construction with respect to seismic activity. This concern can be addressed empirically by reference to the prevalence of straw bale buildings in California which is also known to be an earthquake-prone region, and where local regulations permit this form of construction (King, 2006). However, cares should be taken by considering vapour permeability of the rendering layer constructions. The cement based rendering construction has significant greater allowable shear than the other rendering constructions, but the low vapour permeability of the material may lead to upward trend of moisture content of straw bales within walls in the northern China. The application of the loadbearing straw bale buildings would be subject to the climate conditions and seismic activities of the specific construction locations in northern China.

In China the two major species of straw are rice straw and wheat straw. The use of rice straw may have positive effects which have yet to be demonstrated by research. Rice straw is stiffer than any other straw species in practice (King, 2006; Jones, 2009; Lacinski, 2000; Myhrman, 1998). Using rice straw can produce bales with higher density and stiffness and the rice bales can be empirically demonstrated to increase overall mechanical properties of straw bale walling systems (King, 2006; Jones, 2009). In consideration of mechanical properties of straw bale walling systems, using rice straw may be a better choice than wheat straw in construction of straw bale buildings in China.

However, even though both rice straw and wheat straw would be suitable for load-bearing straw bale buildings in northern China, the use of load bearing straw bale construction may not be approved by the local authority for unfamiliar with the construction method. The in-fill construction of straw bale buildings would be suitable for the development of straw bale buildings in northern China. As there are separate structural frames in the prefabricated straw bale constructions (PSBC), the major considerations of structural reliability of straw bales are the ability to withstand the out of plane load. Resistance to out of plane loads has been shown to be adequate for PSBC walling panels system in existing research (Lawrence *et al.*, 2009a). The PSBC would also be suitable for development of straw bale buildings in northern China.

In comparison with conventional walling materials, the use of straw-based construction materials would use significant lower energy in producing the materials and have much less transport energy cost (Lawrence, 2015). The features of the straw-based building materials make the kind of materials a kind of low embodied

CO_2 building material. In addition to the low embodied CO_2 of straw-based building materials, CO_2 can also be sequestered in the body of straw in the building materials (Sodagar *et al.*, 2011). Plants absorb CO_2 during the photosynthesis to build up the structure of the plants. Straw is the stem of grain-bearing plants and it absorbs carbon through photosynthesis during its growing process and only releases this stored carbon after its decomposition. If the straw is used as a construction material, the effect is that the atmospheric carbon dioxide captured by the straw is sequestered for the lifetime of the building. The carbon sequestration process of the straw-based building materials makes the embodied CO_2 of straw-based building materials carbon negative during the life span of the building (Sodagar *et al.*, 2011). The significant benefit of using straw bales in building industry can also be attributed to the low environment impact at the disposal stage of the building materials. The straw is used in the natural state in the straw-based building materials. The biodegradable feature of straw will cause much less pollution issues than mineral based building materials (Lawrence, 2015).

2.2.3. Durability

Straw, as a part of natural plant, shares a similar construction to that of a cell. The cells of plants consist of cell walls and cell contents. The cell walls consist of micro fibres, pectin and a small amount of protein. During the growth stage, the cell walls transport water and provide structural support for cell contents. After the grain is harvested, the straw stops growing, and the cell walls remain to give structural integrity to the straw at a microscopic level and form the appearance of straws in macroscopic level (Hopkins, 1999). Comparing to timber which is widely used in the building industry, straw is more durable regarding harsh environment than wood. A research carried by Swinker *et al.* (1998) compared the composting characteristics of chopped phone book papers, sawdust and wheat straw. The research showed that straw was the least degraded material in the three materials after 65 days (Swinker *et al.*, 1998). The relative high durability of straw is suitable for building constructions which are expected last for many years.

To verify degradation potential of straw within sealed walls, research has been conducted into monitoring the hygrothermal environment inside the walls and the moisture content of straw bales within walls.
One of the early monitoring research programmes was supported by the Canada

Mortgage and Housing Corporation (CMHC). The monitoring results involved relative humidity and temperature (RH/T) data of straw bale walls at different depths of wall sections (Jolly, 2000). Studies have shown that the RH/T changes within straw bale walls synchronise with seasonal change in the local area of the monitored building (Jolly, 2000).

A separate monitoring programme was conducted in a winery building in California. This research recorded 11 months data of RH/T both within walls and in the building (Straube and Schumacher, 2003), and monitoring results demonstrated that the external surface temperature can be greatly reduced by applying shading in summer (Straube and Schumacher, 2003). Relative humidity within walls is greatly affected by direct exposure to rain(Straube and Schumacher, 2003), with monitoring results presenting higher RH readings in the south facing wall and readings being consistently higher in winter than in other seasons (Straube and Schumacher, 2003).

A purely experimental straw bale wall assembly, completed in Waterloo, Canada, was monitored immediately after construction and has been the object of subsequent research (Bronsema, 2010). This study examined east facing straw bale walls with cement-lime rendering and clay render respectively (Bronsema, 2010). The research used monitoring data to verify a WUFI simulation process (Bronsema, 2010). The thermal modelling would be reasonably accurate if the parameter of absorption of solar radiation is considered in the modelling process (Bronsema, 2010). Moisture modelling is greatly affected by driving rain and the moisture modelling was not as precise as the thermal one (Bronsema, 2010), which also suggested that breathability of render materials is critical for straw bale status with respect to straw degradation (Bronsema, 2010).

A similar result for the properties of render material was shown in research in UK. Use of low vapour permeable rendering material led to an increase in internal RH and would result in straw degradation behind the render (Lawrence *et al.*, 2009c). This research also showed that a rain screen can increase weather resistance of straw bale walls (Lawrence *et al.*, 2009c). The effect of rain screen has total different effect in another research in hot and humid summer area in Furyu in Japan (Holzhueter and Itonaga, 2014), which demonstrated that a passively ventilated rain screen produced elevated RH in lower areas of straw bale walls (Holzhueter and Itonaga, 2014).

Apart from the RH/T monitoring method, the moisture content of straw bale can be monitored by using a wood disc moisture probe (Goodhew *et al.*, 2004). The research presents the applicability of wood-disc sensors in monitoring moisture content of straw bales regardless of temperature change. The wood-disc method was modified by using different timber species (Carfrae *et al.*, 2011).

The existing monitoring research justified that the straw within straw bale walls has potential of degradation in similar climatic areas as the one in northern China. As there is limited research on justification of degradation of existing straw bale buildings in northern China, the durability of straw bale buildings remain uncertain. The following Chapters will discuss the degradation potential of existing straw bale building in northern China and evaluating the effectiveness of the construction detailing in preserving straw from degradation. Due to the durability of straw is one of the key considerations of using straw bale buildings worldwide (King, 2006), the mechanisms of straw degradation and predicting methods of straw degradations are particularly addressed in the follow sections.

2.3. Mechanisms of straw degradation

The previous section shows that the durability of straw bale buildings is the major concern for the development of straw bale construction. This section analyses the durability of straw bale buildings from four aspects: the cellular composition of and micro structure of straw, the presence of microorganisms in straw, the nutrients and environment which support microorganism growth.

2.3.1. Cellular composition and microstructure of straw

To understand mechanism of durability of straw, it is important to analysis the material in microscopic level. The compositions of straw are vary depending on the species of cereal crops. Despite the differences of compositions, the straw feature similar structure. The delicate compositions of straw cell walls are explained by Hopkins (1999). The structure of the cell walls is consisted by several layers which are shown in Figure 2.20. This multiple-layer structural composition of cell walls form defence for straw cells against enzymatic (Hopkins, 1999). The final form of the straw cell wall is the lignification of the walls (Hopkins, 1999). In the process, the lignin in the straw cell walls is inserted by micro level fibres from cellulose (Hopkins, 1999). The completion of the lignification will enhance structural strength of cell walls by forming a pre-stressed skin of the walls (RIBEIRO, 1994) and claims the end of straw cell life (Hopkins, 1999).

Rice straw is high in fibrous lignocellulose and has similar microcosmic architecture as wheat straw. However, the composition of rice straw is different from other crop residues and have better resistance of degradation (King, 2006). Lignin is a class of organic polymers which is essential in forming structural materials for cell walls of plants (Lebo *et al.*, 2001). The effects of lignin involve increase rigidity of plant and resistance of degradation (Lebo *et al.*, 2001). However, even though wood cells contain higher content of lignin, fastest decomposition of wood chips were recorded in the research of Swinker *et al.* (1998). Due to broken wooden particles of wood chips provide better accessibility for microorganisms to nutrients in the wood cells than intact straw (Dresbøll and Magid, 2006), faster degradation of the wood chips were recorded. As a result, the lignin content of straw may not be the critical factor in influencing decay resistance of rice straw (Wihan, 2007).

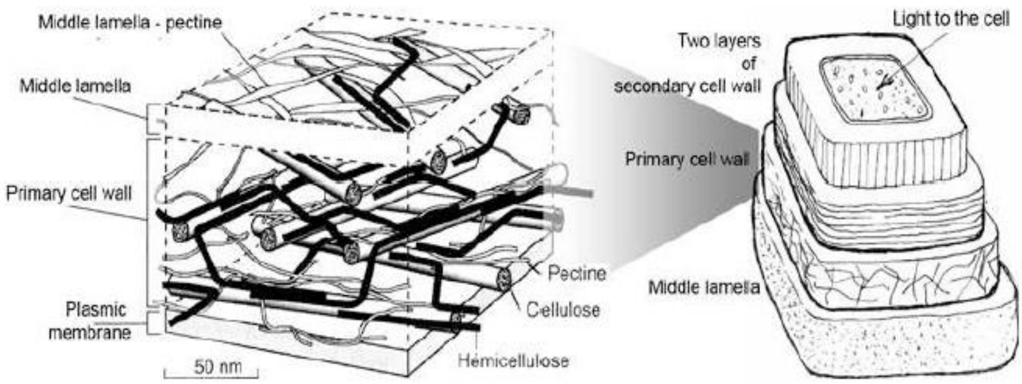


Figure 2.20. Cellulose micro fibres in cell walls. (Hopkins, 1999)

The combination of cell walls results in different structures of straw. The electron microscope images show cell walls of straw are consisted by series of thick lignified straw tissues (Figure 2.21). Hemp straw and miscanthus straw has different ways of degradation with similar chemical compositions (Dresbøll and Magid, 2006). As a result, the decomposition process of straw is crucially determined by the anatomical structure other than lignin level (Dresbøll and Magid, 2006).

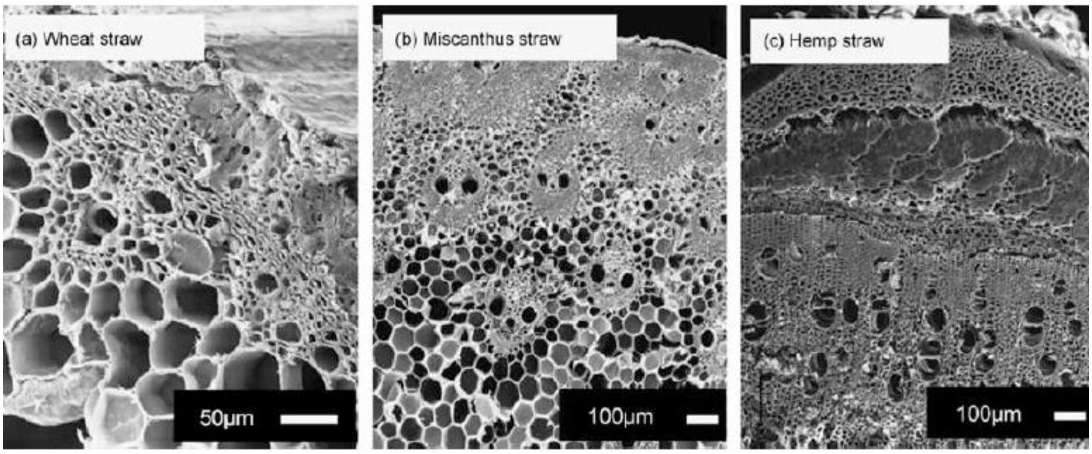


Figure 2.21. Electron microscope scanned image of straw tissues. (Dresbøll and Magid, 2006)

The degradation resistance property of rice straw could be attributed to high silicon content. The silica content of rice straw is relatively higher than other straw (Summers *et al.*, 2003). There is no direct scientific experiment confirming relationship between silica content and degradation resistance; however, studies show that adequate silicon appearance within straw can reduce fungal diseases of straw growing (Mengel and Kirkby, 2001). A reasonable estimation is that the silicon content has positive impact on resistance of fungal degradation of straw.

2.3.2. Nutrients in Straw for microorganism growth

The population of microbiological organisms varies greatly in different places and they can be found everywhere on the planet (Madigan *et al.*, 2008). The determining factor for their population is availabilities of nutrients in certain area. For bacteria and fungi which are mostly considered in straw bale construction, straw is a potential source of nutrients (Summers *et al.*, 2003). Straw is mostly made of carbon, hydrogen and nitrogen. For microorganisms, the compositions of straw are possible food source and can support duplication of microbes and fungi. The deciding factor for microorganism growth is viabilities of nitrogen inside plants (Raun and Johnson, 1999). Other existent ingredients may not affect the decomposition process of straw (Summers *et al.*, 2003).

Even though straw can support growth of fungi and bacteria, it may not be a favourable food source. Research by Dresbøll and Magid (2006) presents effects of nitrogen content on degradation process of hemp straw and clover straw. The results show that low nitrogen content of straw lead to higher resistance of decomposition regarding to microorganism degradation (Dresbøll and Magid, 2006). Summers *et al.* (2003) also have achieved similar results by comparing microorganism populations in barley straw and clover-grass. The nutrient balance is a determining issue in accommodate anaerobic digestion process. Appropriate Carbon to Nitrogen (C: N) ratios for anaerobic decomposition are between 25:1 to 35:1. For straw, the ratio is relatively low. Studies show that typical rice straws which are widely applied in straw bale construction have around 81:1 Carbon to Nitrogen ratio. Summers et al. (2003) report the ratios of straw are range from 70:1 to 120:1, depending on spices and growing environment diversity. The low content of nitrogen in straw is a key factor of high resistance of decomposition of straw (Summers *et al.*, 2003).

2.3.3. Microorganisms in straw

Microorganisms in the straw bales can be either single cell creature or multi-cellular organism (Madigan *et al.*, 2008). Fungi and bacteria are the two class of microorganism which can be found in straw bale buildings. These two microorganisms are introduced into bales when straw is in field before baling process. For straw bale buildings, spores of the microbiological organisms can duplicate within sealed walls under suitable hygrothermal environment (Summers *et al.*, 2003).

Fungi issues in straw may not be serious, according to the research of Hopkins (1999), because fungi needs oxygen to support the growing process, fungi can only inhabit on the surface of straw and they are mostly in the form of spores. Beare *et al.* (2002) have presented researches on bacteria population of barley straw. In their research, the specimen is placed in field for 320 days after harvest (Beare *et al.*, 2002). During the observations, significant bacteria duplication was observed at the beginning month and the increasing become steady for the following experiment duration (Beare *et al.*, 2002). However, despite the growth of microorganisms and activity of microbes on the straw surfaces, the decomposition process of testing straws was recorded constantly in the research (Beare *et al.*, 2002). However, because the microbial population in soil is vastly greater than the one in straw bale walls, the fungi issues should be less concerned in straw bale walls than in soil. In the research of Beare *et al.* (2002), different decomposition levels of straw and the degradation caused by fungi are discussed. The fungi population can be eliminated by rain, UV light and proper treat of fungicides (Beare *et al.*, 2002). AS the population of fungi in straw bales is relative small, it may not be seriously problematic for straw bale walls.

2.3.4. Environment for supporting straw degradation

a. Oxygen availability

There are two kinds of degradation processes within straw bale walls: aerobic degradation and anaerobic degradation (Summers *et al.*, 2003). The oxygen availability of microorganisms inside straws decides what kind of degradation is triggered. The presence of oxygen is an accelerator of straw degradation. The suitable hygrothermal environment will lead to readily aerobic decomposition of straw (Zhu, 2007). However, straw bale walls are isolated from external environment by render layer and oxygen concentration can only support initial aerobic degradation of straw (Thomson and Walker, 2014).

The relative sealed environment within straw bale walls is mostly provided by rendering constructions. Even though different kinds of rendering constructions have various permeabilities for water and air transmittances, they all can provide relative sealed environment for straw bales (King, 2006). Even though relationships between properties of rendering construction and decomposition resistance of straw bales are not fully understood in current researches (Wihan, 2007), all rendering materials have ability in limiting moisture content and achieve similar air tightness inside straw bale walls (Bergeron and Lacinski, 2000). This property of rendering constructions can gradually reduce oxygen level inside straw bale walls and lead to anaerobic degradation (Summers *et al.*, 2003).

In the process of anaerobic degradation, straw will have much longer decomposition process than the aerobic one. As most bacterial need oxygen to trigger the biological reaction which can transfer mineral nitrogen to proteins, the active microorganisms are in low quantity (Hopkins, 1999) in straw bale walls sealed by rendering constructions. As a result, the decomposition process of anaerobic is much longer than the aerobic one.

b. Temperature and Moisture

As discussed in last section, the major decomposition inside straw bale walls is the anaerobic degradation. In the process of the anaerobic degradation, there are three key elements in triggering the biological reactions: supplement of feedstock, suitable temperature and high level of moisture. For straw bale walls, straws provide allowable food for microorganisms. In this case, levels of moisture and temperature become the determining factor for durability of straws inside walls (Summers *et al.*, 2003).

The environment inside straw bale walls can protect straw from hostile activities of microorganisms. Bacteria and yeasts can only duplicate in high moisture condition and other than this, yeasts also need light to process the biochemical reactions which are essential for growth of microorganisms (Dresbøll and Magid, 2006). Considering the environment inside a straw bale wall, rendering construction form a barrier between straw bales and atmosphere. As a result, relative dry and completely no light conditions can be achieved and the environment in straw bale walls will not accommodate growth of the microorganisms. However, there may be some issues for straw bale walls in the situations with presence of liquid water between rendering constructions and straw bales. The straw bale walls which are exposed to high humidity and great differential temperature on both sides may lead condensation in the straw bales. Straw will be degraded by long time exposure to liquid water.

Favourable temperature is important in the process of anaerobic straw decomposition (Bergeron and Lacinski, 2000). There are two major ranges of temperatures in the digestion process (Bergeron and Lacinski, 2000). The mesophilic digestion is triggered between 30 °C to 38°C and the thermophilic decomposition occurs around 49°C - 57°C (Song *et al.*, 2004). When temperature drop lower than freezing point, because water transform from liquid to ice, decomposition will not happen due to frozen water (Summers *et al.*, 2003). Also, bacteria and fungi cannot survive in temperatures which are above 65°C (Summers and Beall, 2000).

2.4. Predicting straw degradation

As discussed in last section, the hygrothermal environment within straw bale walls and moisture content of straw bales are the two critical factors for straw degradation.

This section reviews existing methods for predicting the critical hygrothermal conditions within straw bale walls and the critical moisture content of straw bales for straw degradation.

2.4.1. Isopleth

The isopleth system is design to describe specific reaction of growth of different mould species in different hygrothermal environments (Magan and Lacey, 1984). By considering the degradation characteristics of building materials, the isopleth is developed to be suitable for predicting degradation of building materials regarding various hygrothermal conditions (Sedlbauer, 2002). Sedlbauer (2002) examined 12 different incubation units with different hygrothermal conditions to examine mould growth of different building materials for 100 days. Sedlbauer (2002) categorises building materials against four levels of substances for mould growth (Table 2.2) and straw is categorised in the Substrate category II in this research (Sedlbauer, 2002). Based on the category of building materials, isopleths of limiting conditions of mould growth of each category is produced by Sedlbauer *et al.* (2011). The lowest isopleth for mould growth (Figure 2.22) is also achieved to describe the border conditions for supporting all mould species related to building materials at optimal media (Sedlbauer, 2001).

Table 2.2. Category of substances for mould growth. (Sedlbauer, 2002)

Substrate category 0	**Optimal biologic culture medium.**
Substrate category I	Biologically recyclable building materials like wall paper, paper facings on gypsum board, building materials made of biologically degradable raw materials, material for permanent caulking.
Substrate category II	Building materials with porous structure such as renderings, mineral building materials, certain wood species as well as insulation material not covered by I.
Substrate category III	Building materials that are neither biodegradable nor contain any nutrients.

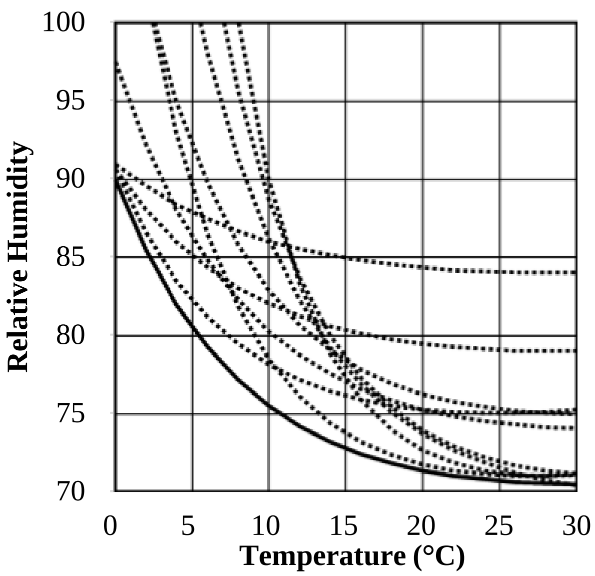


Figure 2.22. Lowest isopleth for mould growth (LIM 0). (Sedlbauer, 2001)

Based on the previous research of Sedlbauer (2002), a modified system of isopleths has been developed by measuring different building materials (Sedlbauer *et al.*, 2011). Sedlbauer *et al.* (2011) categorised risks of mould growth in three colours and the lowest triggering conditions for any mould growth at optimal media (LIM 0) (Sedlbauer, 2002). Red colour presents high risks of mould growth, yellow colour represent moderate concern of mould growth and the green colour represents no decomposition risks of the examined building materials (Sedlbauer *et al.*, 2011). The isopleth for predicting decomposition of wheat straw is shown in Figure 2.23. There is no research available on the decomposition isopleths of rice straw. Rice straw has been shown by Clynes (2009) to be more durable and to have a longer duration of decomposition than wheat straw or barley straw. This research result is also seen in straw bale building practices in California in US (King, 2006). The isopleth for predicting decomposition of rice straw would be potential interests in further research.

The isopleths may not predict the degradation of straw bales within straw bale walls. The degradation isopleths are developed to predict mould growth on surface of building materials (Sedlbauer *et al.*, 2011). Oxygen availability of the experimental methods are at the levels of air oxygen concentration (Sedlbauer *et al.*, 2011). The experimental environment of the degradation isopleths is greatly different from the low-oxygen environment in straw bale walls. The research of straw degradation in UK show that straw is in good condition in the environment which is identified red area in the degradation isopleths (Thomson and Walker, 2014).

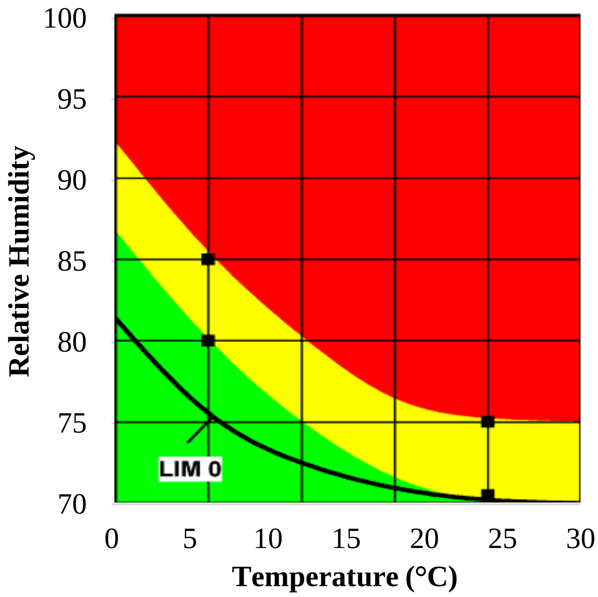


Figure 2.23. Isopleth system of wheat straw. (Sedlbauer *et al.*, 2011)

2.4.2. Sorption isotherm

Straw is a plant fibre with similar micro cellular structure to wood cells (Strømdahl, 2000). As with wood fibres, straw is also a porous material (Strømdahl, 2000). The porous nature traps moisture from the surrounding air regulating fluctuation in RH (Stamm, 1964) and straw is commonly referred to as a hygroscopic building material (Carfrae, 2011). The moisture content of straw tends to equilibrate with the RH of the surrounding environment in the immediate vicinity (Skaar, 1988). As with other hygroscopic materials, the water vapour sorption of straw has five phases (Figure 2.24): Single layer of adsorbed molecules, multiple layers of adsorbed molecules, interconnected layers, free water in capillaries and supersaturated (Straube, 2006).

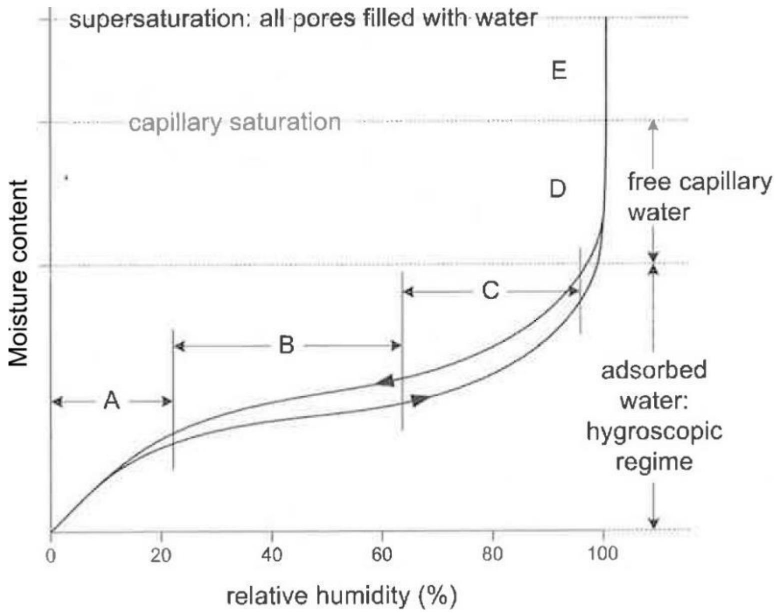


Figure 2.24. Phases of moisture content of hygroscopic materials. (reproduced from (Straube, 2006))

Plant fibre and wood have two unique features in high RH situations which are not observed with inorganic hygroscopic materials; the fibre saturation point and capillary condensation (Skaar, 1988; Stamm, 1964). Both cell walls and cavities between cells can adsorb moisture vapour in high humidity conditions (Stamm, 1964). To describe the stage at which cell walls become saturated, the term fibre saturation point is used (Skaar, 1988). The fibre saturation point is the moisture content at which the cavities between cells contain no water but the cell walls are fully saturated (Skaar, 1988). It is difficult to estimate the fibre saturation point of plant fibre and wood in practice (Strømdahl, 2000). The normal assumption is that the fibre saturation point of wood occurs at a moisture content of 27-32% (Stamm, 1964; Skaar, 1988). As RH increases, water vapour can condense on the walls of pores in plant fibres (Skaar, 1988). This capillary condensation contributes a significant amount to the moisture content of plant fibre when RH is over 70% (Strømdahl, 2000). However, because of the dense structure of cellulose chains between wood cells, the capillary condensation is likely to occur after the moisture content exceeds the fibre saturation point (Skaar, 1988). The capillary condensation is also affected by the pore structure and size of plant fibre and wood cell (Strømdahl, 2000).

The sorption isotherm describes the direct relationship between moisture content of hygroscopic materials and the RH in surrounding environment (Hens, 2012). The isotherm is commonly achieved by using either a desiccator method or a climatic chamber method in laboratory (Institution, 2013), however Hedlin (1967) used a jacketed air bath to demonstrate the isotherms for five different grain straw species. The desiccator method uses saturated salt solutions to create a known RH in a sealed container at 23℃ and the climatic chamber uses an external source of water vapour to adjust the RH level in a sealed chamber (Institution, 2013). Based on the experimental results, Hedlin (1967) produced an equation to predict moisture content of straw:

$$\varphi = \frac{1-K_c(1-\frac{C}{C_S})}{1+[\frac{\frac{C_S}{C}-1}{n}]ay^{3/i}} \quad (2.1)$$

Where:

$\varphi = relative\ humidity$

$C = moisture\ content\ at\ relative\ humidity\ \varphi$

$C_s = fibre\ saturation\ moisture\ content\ (400\%)$

$n = C_s/C_{50\%RH}$

$K_c = 0.0227$

$i = 1.6$

The equation was calibrated by straw species including oat straw, barley straw, flax straw and two types of wheat straw at 14 different RH levels at 70 ℉ (21.1 ℃) (Hedlin, 1967). The equation cannot convert RH in the surrounding environment to moisture content without air temperature, meaning its usefulness in predicting moisture content of straw bales in walls is limited. However, the effects of temperature have little effect on water absorption of straw in the day to day life of straw bale buildings. Strømdahl (2000) used a climatic chamber to investigate the water absorption properties of four plant fibres. The sorption isotherm of wheat straw showed no significant differences at 20℃, 40℃ and 60℃. Compared with the isotherms at 20℃ and 40℃, the moisture content of wheat straw is slightly lower at 60℃. As the air temperature is not likely to reach 60℃, this isotherm is not relevant for predicting moisture content of straw within straw bale walls. Experimental results show no significant differences of moisture content within the straw at temperatures of 5℃, 15℃, 25℃ and 35℃ (Duggal and Muir, 1981). Based on the experiment, Lawrence *et al.* (2009b) modified the Hedlin (1967) equation by ignoring effects of temperature difference. The modified equation has similar results in predicting moisture content of wheat straw (Figure 2.25). The simplified equation is shown as:

$$C = \frac{C_s}{1+n(\frac{K_m}{\varphi}-1)^{i/3}} \text{ (2.2)}$$

Where:

$C = moisture\ content\ at\ relative\ humidity\ \varphi$

$C_s = fibre\ saturation\ moisture\ content\ (400\%)$

$\varphi = relative\ humidity$

$n = 44$

$K_m = 1 - K_c = 0.9773$

$i = 1.6$

Carfrae (2011) has reviewed published sorption isotherms for straw (Figure 2.26). Apart from the isotherms of Sain and Broadbent, all the isotherms are relative similar. Sain and Broadbent (1975) have produced isotherm for rice straw. Compared to research on wheat straw, the research by Sain and Broadbent (1975 presents a different isotherm for rice straw. Rice straw has less water adsorption than wheat straw at all relative humidity levels. However, the research method is not in accordance with current standards and the differences may be because of differences in the research methods used. There is at present no published research available showing sorption isotherms for rice straw following current scientific methods.

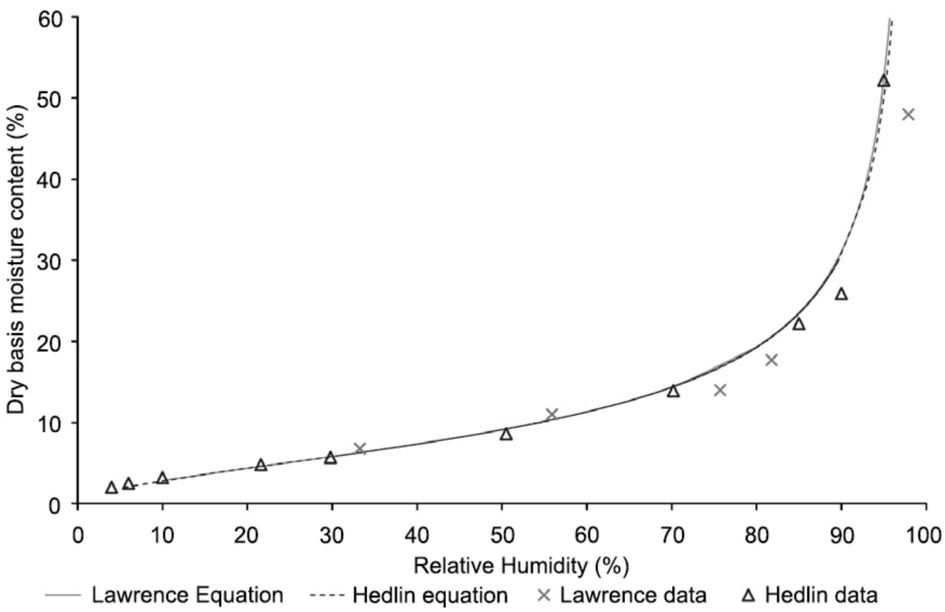


Figure 2.25. Comparison of Lawrence *et al.* (2009b) expression and Hedlin (1967) equation.

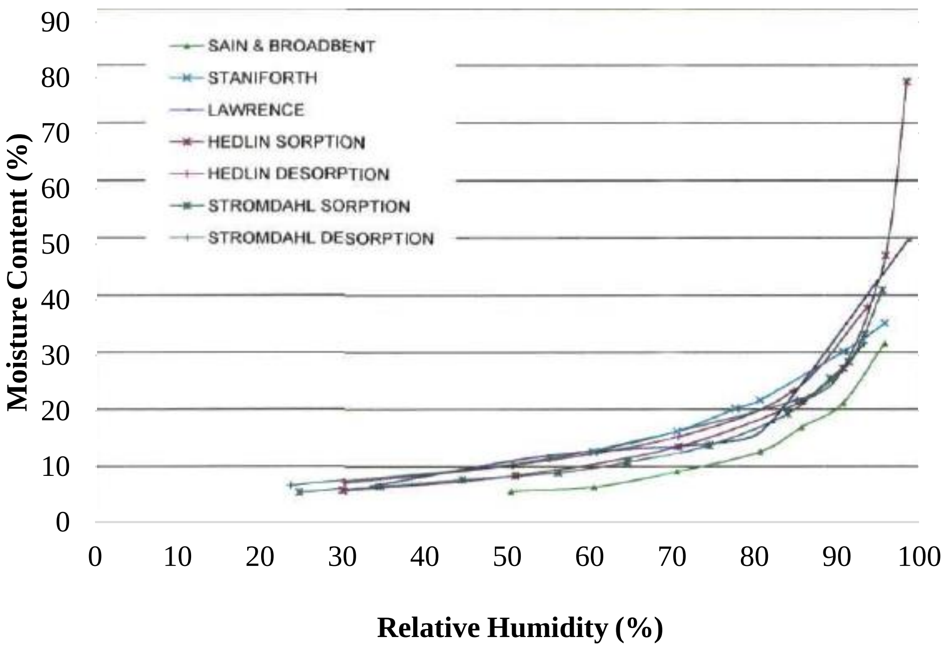


Figure 2.26. Reviews of published sorption isotherm of straw. (Carfrae, 2011)

The maximum allowable moisture content of straw bales is between 20%-25% for construction purpose before decay is likely to begin (King, 2006; Myhrman, 1998; Magwood, 2003; Jones, 2009). However, wheat straw is likely to be capable of withstanding transient high moisture contents provided it is allowed to dry out subsequently with no apparent damage under typical maritime climate in UK (Carfrae, 2011). The short period maximum moisture content is around 37% which is the capillary saturation point of straw (Carfrae, 2011). The moisture content can be converted to relative humidity by using the sorption isotherm of straw. Straw can be exposed in a situation of 93%-96% relative humidity for short time and it will not have notable decomposition. The research presents a wider allowance for straw bale construction in the UK. Strømdahl (2000) achieve sorption isotherms of flax fibres, hemp fibres and wheat fibres in 20C°, 40C° and 60C° (Strømdahl, 2000). Much lignin content of wheat straws may be the reason of higher saturation value of wheat straws than other two plant fibres (Strømdahl, 2000). Considering the influence of temperature on the wheat straw sorption isotherms, the wheat straws show lower moisture content when they are exposed in higher temperature within certain relative humidity (Figure 2.27).

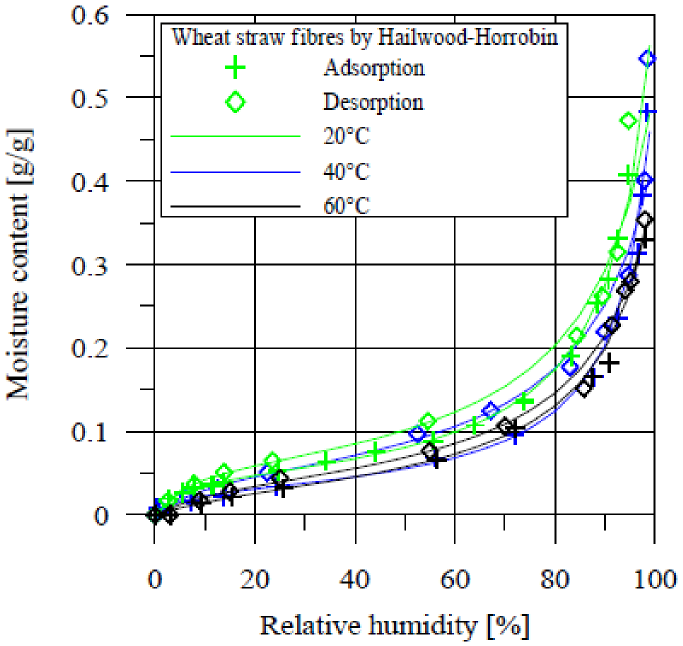


Figure 2.27. Sorption isotherms of wheat straws within different temperature. (Strømdahl, 2000)

Even though the isothermal model can predict moisture content of straw within walls, cares should be taken in applying the model in actual situations. The water adsorption process of straw require certain amount of time to reach equilibrium in specific relative humidity levels. Current isothermal models are based on equilibrium moisture content of straw in various relative humidity levels (Hedlin, 1967; Lawrence *et al.*, 2009b). However, actual air relative humidity levels in straw bale walls change rapidly that equilibrium moisture contents are hardly achieved in real situations. The amount of time required for straw to reach fully equilibrium moisture content is research by Bigland-Pritchard (2006). Fully dried straw was placed in an environment with constant increasing relative humidity levels (Bigland-Pritchard, 2006). The results have shown that straw require 10 to13 hours to reach 90% equilibrium moisture content in the relative humidity levels of its surrounding environment (Bigland-Pritchard, 2006). As a result, modified isothermal models on basis of not fully equilibrium moisture content of straw will draw closer may to moisture content of straw within straw bale walls in real situations.

2.5. Summary

The current knowledge and understanding of straw bale construction is reviewed at the beginning of this chapter. Because both wheat and rice are widely cultivated in northern China, both types of straw are widely available for use as a building material. Straw is typically used in the form of bales in straw bale buildings using either laid flat or laid on-edge stacking methods. The literature shows that straw bale walls using the laid on-edge stacking method theoretically have 25% to 30% lower thermal conductivity than if the laid flat method is used. However, this effect may not be as significant in full scale construction. In addition to straw bales, there are three other elements that are key contributors to successful construction of conventional straw bale walls.

- The toe-up foundation isolates the straw bale from rising damp damage and ensures that no moisture builds up beneath first layer of bales;
- Pinning systems that connect bales guarantee the stability of straw bale walls before a render is applied and increases the buildability of straw bale stacking;
- Rendering the straw bale walls provides structural stability and breathability to the straw bales inside the walls and protects them from the external environment.

Informed by conventional straw bale walling construction, prefabricated walling panels using structural timber frames have been developed and applied worldwide. Prefabricated walls tend to feature better quality control and reduce the impact of adverse weather conditions during the construction phase compared with on-site construction of straw bale walls.

Straw bale construction was first introduced into northern China by ADRA in 1998 and by the time the project had concluded more than 600 straw bale buildings had been constructed. These buildings feature low heating requirement and low construction cost as reviewed in the relevant literature. Apart from the ADRA project, only one other straw bale building is known to have been constructed, which is an experimental building completed in 2010. There are no known straw bale building projects currently being undertaken in China.

The potential risks of using straw bale buildings in northern China were also considered. Both loadbearing straw bale walls and non-loadbearing straw bale walls have been shown, through existing research, to be structurally safe in seismic active regions. However, there is no existing research on the structural properties of straw bale walls which comply with Chinese standards. Non-loadbearing straw bale buildings would be a more suitable approach for development of this building type in northern China. The issues of standards and regulations are discussed in the second part of this section. Even though there is no design code specifically regulating straw bale buildings, such buildings have the potential to pass the standards including codes for fire risk and regulations for energy saving in China. Because of the low carbon emission of straw bale buildings which is beneficial to the carbon reduction commitments of China, this type of building would be supported by the Chinese government through further amendments of building regulations.

The potential durability of straw bale buildings taking into account of local climatic conditions in northern China is considered. Existing research evaluating the durability of straw bale buildings is mostly based monitoring actual buildings. Research on this type of building in Canada and Japan under similar climatic conditions has identified the potential for the degradation of straw in these locations. As straw is a bio-based building material, the susceptibility to degradation of straw is vital to understand in order to assess the overall performance of this building type. As a result, uncertainty of the susceptibility to degradation inside straw bale walls is the key limitation for development of this building type in northern China.

As degradation of straw is a critical threat to this type of building, detailed discussions of the mechanism of this process are included which take into account the cellular composition of straw, microorganisms, nutrients inside straw and the supporting environment for the degradation process. Due to high silica content of straw and low nutrient content of straw, it is a relatively durable material in the context of microorganism damage. The degradation process of straw inside straw bale walls involves both initial aerobic degradation and long term anaerobic degradation. As a result, the moisture levels and favourable temperature for anaerobic degradation is the key element for straw durability inside walls. Even though aerobic degradation can only happen in the short term immediately after the application of the render layer, because this degradation process is much more rapid than anaerobic degradation, the impact of aerobic degradation can be more significant.

This chapter reviews existing prediction models for straw degradation in context with the supporting environment of the process. The degradation isopleth model considers the hygrothermal environment for trigging straw degradation. Different hygrothermal environments are classified into three categories to indicate levels of straw degradation. The green category indicates no degradation whereas the yellow category and red category represent moderate risks and serious risks for straw degradation respectively. The isothermal model converts the different levels of water sorption of straw into moisture content of straw to allow prediction of straw degradation. The initial model considers both the effects of temperature and surrounding humidity levels. Due to the relatively insignificant impact of temperature on the process, the model is later modified by excluding the temperature factors whilst maintaining a similar accuracy of prediction.

Concluding from the literature, there are three major issues for developing straw bale buildings in northern China. The research on existing straw bale buildings in northern China mainly focusses on the energy efficiency of the buildings and the suitability of the building type. There is limited literature that examines the building which takes into account discussion of the construction technique and the investigation of current conditions of the buildings. The second issue is the degradation potential of straw bales within walling systems in the climatic condition in northern China. There is no existing research on the likelihood of degradation of straw in the climate of northern China. The use of straw bale construction can only be validated by examining the decay potential of straw within walls and making use of appropriate detailing and methods to mitigate against straw degradation. Thirdly, due to large quantity of rice production, rice straw would be a major source of raw material for straw bale construction in northern China. As wheat straw is predominantly used in existing construction of straw bale buildings, this species of straw is well understood in existing research. However, there is limited literature focussing on the characterisation of rice straw. As the degradation potential of straw bale buildings is a major issue for the development of the building type in northern China, characterisation of the water sorption properties of rice straw is also critical if this material is to be used in construction.

3. Methodology

The existing literature, discussed in Chapter 2, showed that straw has a notable susceptibility to degradation within straw bale buildings in climatic conditions comparable to those found in northern China. In order to understand the susceptibility to degradation of straw bale buildings, and therefore the risks involved in their adoption, the approach and resulting experimentation methodology and approaches of this research have been designed into three stages:

Firstly, the moisture adsorption property of straw and the degradation potential of straw are investigated. Two varieties of straw are initially individually considered, followed by their interaction with a lime render. The laboratory experiments contribute to the understanding of properties of straw as a kind of building material.

Secondly, straw bale buildings were constructed in northern China around 20 years ago and offer a potential to understand in-situ performance. The approach to the building investigations and method to evaluate the design of the current state of the art are subsequently discussed.

Thirdly, In-situ research and development of a newly built straw bale building, based on the understanding of previous two stages is developed. The newly built straw bale building is designed merely for experimental purposes and thus the results of the in-site research excludes issues raised by human factors.

3.1. Degradation characteristics of straw

As discussed in section 2.3 and 2.4, the hygrothermal environment inside straw bale walls and the moisture content of the straw are the two major factors in the susceptibility to degradation. This section firstly introduces the research methods used to examine the microscopic structure of straw and the moisture adsorption properties. Because of concerns over straw degradation under potentially high temperature and high humidity conditions inside the walls, a separate experiment is designed to investigate the susceptibility to degradation within a typical build up including the addition of a render.

3.1.1. Moisture adsorption properties of straw

The moisture adsorption properties of straw are intrinsically connected to the microstructure of the material. Therefore the microstructure of rice straw and wheat straw are first investigated and compared. This informs the moisture adsorption properties which are subsequently measured.

a. Materials

Two straw species, rice and wheat straw are considered. The rice straw is sourced from northeast China and the wheat straw is from England. The rice straw and wheat straw were studied both in the form of straw bundles and short lengths of straw (chips) to suit the different experimental methods used for measuring the sorption isotherm of straw.

b. Microstructure characteristaion

The outer surface and cross-section of the two straw species, were imaged with a JEOL SEM6480LV Scanning Electron Microscope (SEM) at an accelerating voltage of 10kV. Following initial drying the specimens were gold coated in a sputter coater for five minutes.

c. Sorption Isotherm

The study followed BS EN ISO 12571:2013, using both the climatic chamber method and the desiccator method. A dynamic vapour sorption (DVS) machine was used to produce a continuous isotherm for the climatic chamber method. This allowed for comparison of both methods. Straw chips were used in the DVS method and small bundles were used in the desiccator method. The bundles were around 20g in mass, 40mm in diameter and 160mm in length. The density of the bundles was set at around 110kg/m^3 to reflect the density of straw bales which are used in construction. VS tests samples consisted of two chips in each test. One chip consisted of only the sheath, and the other chip included a higher density node in order to be fully representative of the material. The straw chips weighed 3-5g and were 40-60mm in length. Both forms of straw were dried at 105ºC until no further mass change occurred, at which point they were weighed to establish a zero moisture content mass.

A DVS machine was used to produce a continuous isotherm for the climatic chamber method. The DVS equipment used for this study was the DVS Intrinsic, manufactured by Surface Measurement Systems Ltd. The advantage of the equipment was that it was capable of producing a highly sensitive and rapid sorption isotherm and desorption isotherm.

The specimens were examined at relative humidity levels between 0% - 95% at 5% relative humidity intervals whilst the temperature was maintained at 23°C. The method used two different mechanisms to establish the time intervals at which to change steps of relative humidity levels. Between 0% and 65% RH, changes were based on the change of specimens in mass over time (dm/dt). When dm/dt < 0.002 g/min the change to the set RH point was initiated. Between 70% RH to 95% RH, because the rate of adsorption of both species of straw becomes significantly slower, changes were made at 1600 minute intervals in order to achieve a full isotherm within an acceptable time period.

The specimens consisted of single pieces of rice straw and wheat straw. It was hypothesised that the cross section of straw might have an impact on the water sorption property of straw. The research differentiated the adsorption isotherm of the two straw species by considering microstructural differences between the outer surface and cross-section of straw. Each specimen was subjected to three sorption/desorption cycles and then the ends were sealed with wax, and a further three sorption/desorption cycles were performed (Figure 3.1).

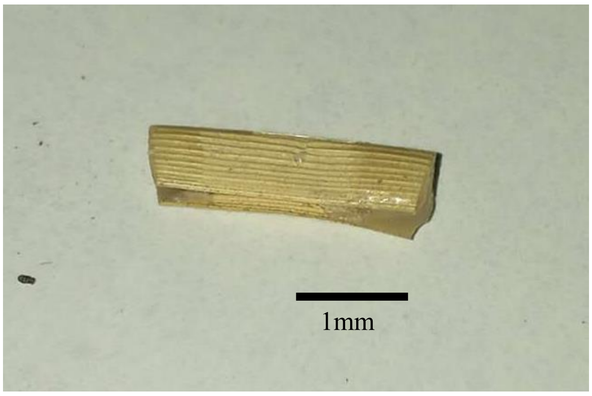


Figure 3.1. Rice straw chip with wax sealing in edge in the DVS Intrinsic2.

The desiccator method was used in this study for RH levels where fibre saturation was expected to occur. Two saturated salt solutions were used to produce sorption isotherms in a high relative humidity environment. The saturated salt solutions used in the research were ammonium sulfate solution and potassium sulfate solution to produce RH 81.13%±0.28% and RH 97.42%±0.47% respectively (British Standards Institution, 2013). Small straw bundles were used in the desiccator method. There were three rice straw bundles and three wheat straw bundles at each humidity levels as shown in Figure 3.2. The specimens were placed in sealed containers with different saturated salt solutions. The accuracy ranges of the relative humidity provided by saturated salt solutions are listed in the BS EN ISO 12571:2013, installation of temperature and humidity sensor were not required in the desiccators method in the standard (British Standards Institution, 2013). In consideration of monitoring the hygrothermal environment within the two setups of desiccator method, a HTC-1 temperature and humidity sensor was placed within the containers. The sensors have accuracy of ±0.3℃ from -25℃ to 85℃ and ±1%RH@50% (±3% 0%-95%RH). The containers were maintained at a temperature of 23 °C. These HTC-1 sensors confirmed that the desired humidity of the environment was achieved from the respective salt solutions at the given temperature.

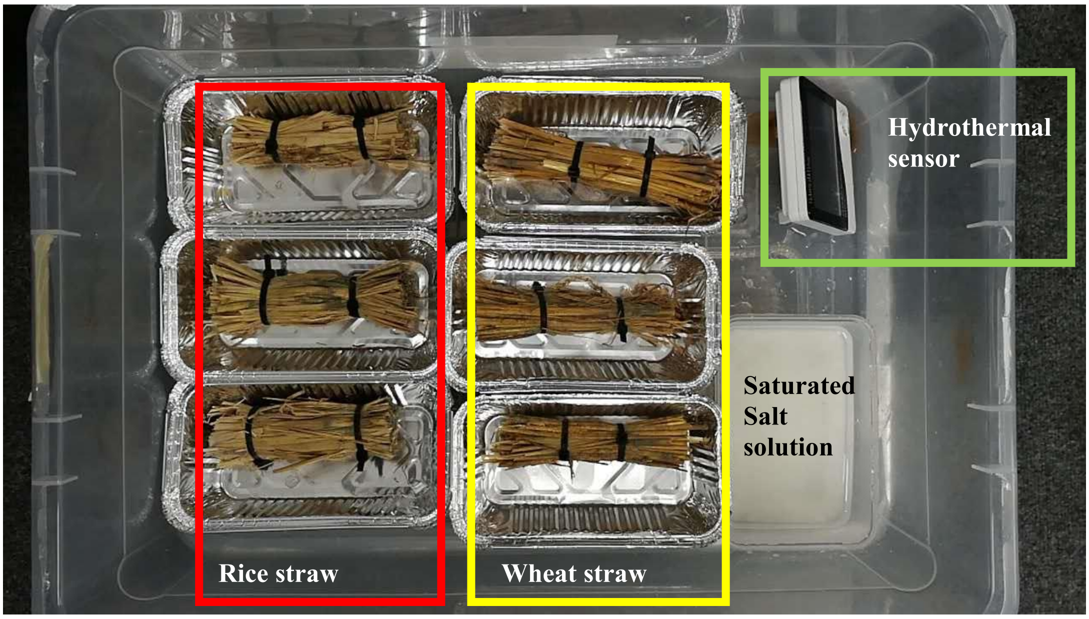


Figure 3.2. Desiccator method equipment in the research.

For each salt solution, six specimens (three rice straw and three wheat straw) were studied. The specimens were maintained at these conditions for a period of 6 weeks, at which point they were weighed, to the nearest 0.01 g to establish their moisture content. Considering the average mass of the bundles, this represents a potential error of 0.1 %. The specimens were then replaced in the container for a further 24 hours and re-weighed. This process was repeated until the change in mass was less than 0.1% between readings. At this time it was established that there was no further mass change and it could be assumed that equilibrium had been achieved (British Standards Institution, 2013).

3.1.2. Susceptibility to degradation of straw bale buildings

To assess the possibility of degradation induced by the high RH and high temperature conditions, an experimental investigation was designed to represent a typical wall build-up. There are no published methods for the tests. The experimental results will be compared with onsite visits of the experimental building to access degradation potential of straw within straw bale walls.

The investigation of degradation potential of straw uses a climatic chamber to replicate the environment within Northern China. The climatic chamber was manufactured by ACS and the model is DY 110 (C). Concluding from the monitoring research, the conditions of climatic chamber is set up at 95% RH and 35℃ to represent the potential peak daily mean temperature and peak daily mean RH. The duration of the experiment was designed to be slightly longer than the summer months would be encountered in the monitoring research. The duration of the degradation experiment was designed to be 12 weeks. The duration includes an allowance for an initial 2 weeks for moisture build up within the sealed straw bales and the following 10 weeks which represent typical summer months in northern China.

Straw bales and lime render were constructed in three transparent boxes to represent walling constructions of straw bale buildings (Figure 3.3). Both rice straw and wheat straw were used in different wall constructions. The straw used in the experiment had the same source as the straw used in the moisture adsorption research. The straw was baled in small bundles and placed both parallel and perpendicular to the lime render to represent the laid flat stacking method and the laid on-edge stacking method in typical construction of straw bale buildings. A RH/T sensor was installed in the straw bundles in each specimen (Figure 3.4). The thickness of lime render is 50mm in the construction of specimen. The adjacent area between the lime render and the transparent boxes were sealed by wax to avoid direct pass of environmental RH to travel into the straw in the specimen. The transparent boxes of the walling constructions were labelled into small rectangle to identify possible area of straw degradation in the research.

The specimens were placed in controlled climatic room (80% RH and 20℃) for one week to cure the lime render. The cured specimens were then placed in low temperature (40℃) oven for one week to reach lower than 85% initial RH @ 30℃ before placing specimens in climatic chamber. During the 12 week experimental period, the conditions of straw were visually checked once a week, and at the beginning of week 4, once a day for the following 8 weeks.

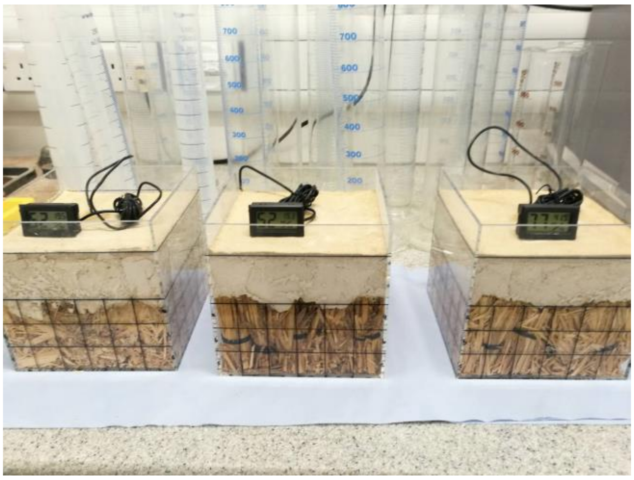


Figure 3.3. Section of walling construction in the degradation potential experiment.

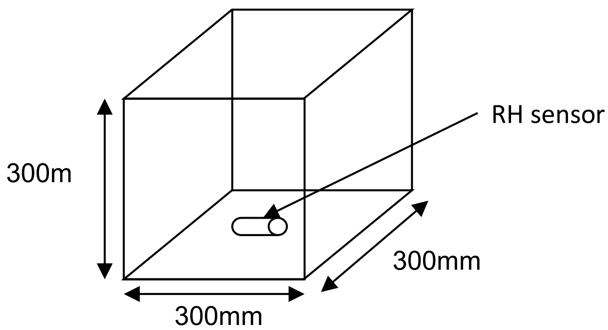


Figure 3.4. Diagram of experiment specimen and sensor set up.

3.2. Existing straw bale buildings

The existing straw bale building projects have been discussed in the section of 2.1.5. Since the completion of these buildings, there have been limited investigations evaluating the status of the buildings. This section discuss the research method and approach of investigating these buildings.

The target projects being analysed were the ADRA project in Jiamusi and the following steel frame farmhouse with infill straw bale walls in Baishan. The ADRA project in Jiamusi was the first straw bale project in China. Following straw bale buildings in the ADRA projects were broadly similar to the initial project in Jiamusi. Inspired by the building technique applied in the ADRA project, an experimental straw bale building with steel frame was constructed in Baishan, Jilin Province in 2010. The project was the only known constructed straw bale building other than the straw bale buildings in the ADRA project. The places of the two project are shown in Figure 3.5.

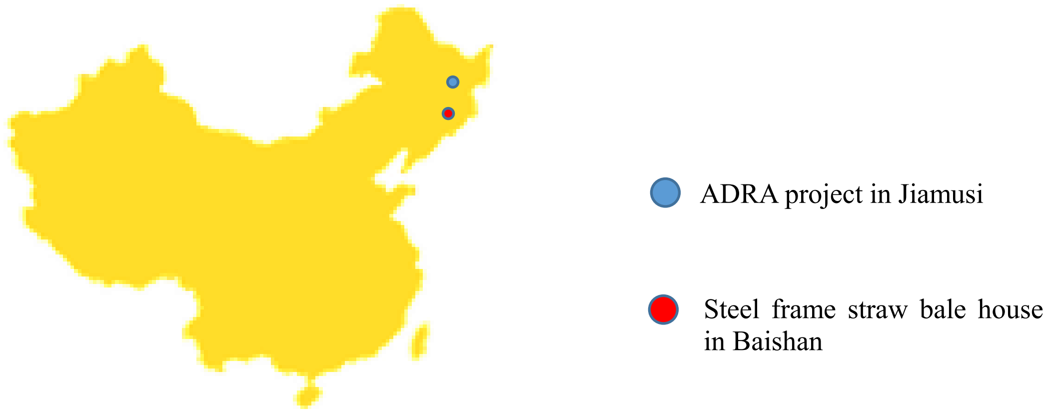


Figure 3.5. Area of the researched projects of straw bale building in China.

There are two stages of the investigation of the existing straw bale buildings. The designs of the buildings were first collated to allow for analysis, with a focus on bale selections, walling design and render selections. Secondly, site visits of the buildings were conducted. The site visit of the straw bale buildings focused on evaluation of current status of the straw bale buildings in regards to the construction quality of the walling, existing issues for straw degradation and the feedback of local residents. Cultutally, local residents preferred to have conversations rather than filling questioners. The questions involved in the conversation with local residents are presented in Table 3.1.

Table 3.1. Questionnaire for on-site visit to existing straw bale buildings.

Question
How long have you lived in the building?
Do you know the design manual of your straw bale building?
How often do you maintain the walling construction of your building?
How do you think of the straw bale building you live in?
What is your daily routine of life? (i.e. how you use your building?)
What is your plan with your straw bale building in further?
If you would move to a new dwelling, would you prefer a straw bale building or masonry building (typical farmhouse in northern China)?

3.3. Experimental straw bale building and set up of monitoring

3.3.1. Geographic and meteorological characteristics of the building site

The experimental straw bale house was constructed in Changchun, in the Jilin province of northeast China (Figure 3.6 and Figure 3.7). This section introduced the geographic and meteorological characteristics of the area of Changchun. The feasibility of using straw bale constructions in this area is analysed in Chapter 6.

Figure 3.6. Area of Changchun in China.

Figure 3.7. Building site of experimental building (43°47'29.5"N, 125°24'26.4"E) in Changchun. (Google Map, 2018)

Changchun is subject to a typical temperate monsoon climate. In the national thermal design code of civil buildings (GB50178-93, 1994), the area is identified in the severe cold climate zone which is part of the temperate monsoon climate zone. Temperature peaks at around 30℃ in the area from June to August and drops to below freezing after late October annually (Figure 3.8). The highest monthly air humidity level is 88% and it appears in January (Figure 3.9). The monthly humidity levels are from 63% to 72% in summer during which the highest temperature appears.

The climatic features of Changchun represent three typical climatic characteristics in northern China: Firstly, both the air temperature and humidity are at high levels in summer months. The daily high temperatures are around 30℃ in summer months. Due to the features of template monsoon climate, rainfalls are expected mostly in summer months which lead to the high air humidity. Secondly, as lowest rain potentials and air humidity are expected in spring months in template monsoon climate areas, the spring can be identified as a “dry” season in northern China. However, as air temperatures begin to rise up above freezing in March, melting snow increases humidity levels in northern China. Comparing the air humidity levels in April and May, the monthly average humidity of March is significantly higher than the one in April and May in Figure 3.9. Thirdly, the air temperatures in northern China are expected below freezing during the whole winter months and highest monthly air humidity levels present during the same period of time. However, the high air humidity levels does not result in humid environment inside and outside buildings. As the low temperatures decrease absolute water vapour pressures in the air, the relative humidity levels in winter months are significant higher than other months annually in northern China. As a result, the winter months in norther China are featured cold and dry (GB50178-93, 1994).

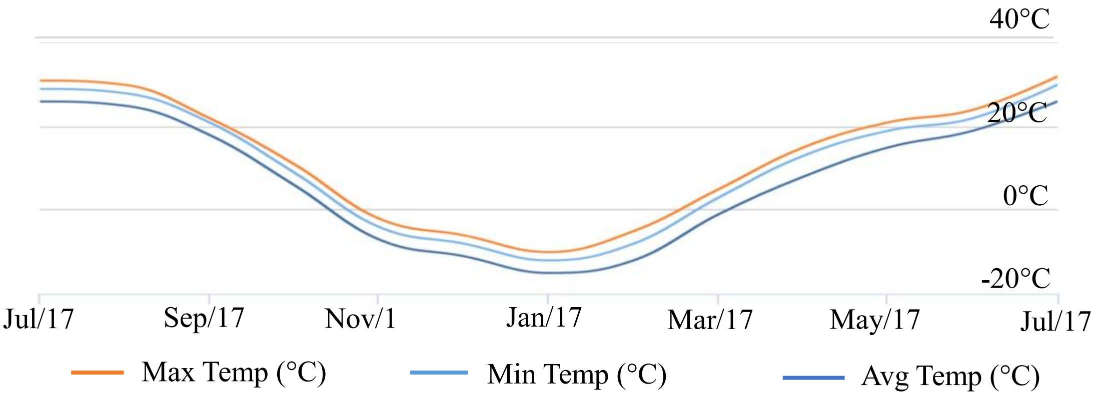


Figure 3.8. Average monthly maximum temperature, minimum temperature and average temperature in Changchun from July 2016 to June 2017. (World Weather Online, 2017)

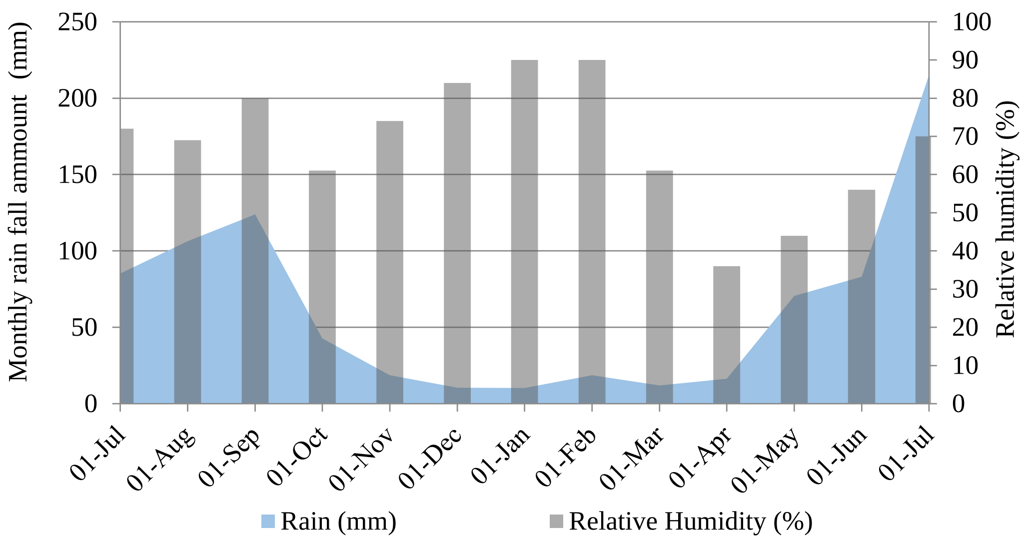


Figure 3.9. Average monthly Humidity and rain fall in Changchun from July 2016. (World Weather Online, 2017).

3.3.2. Designs of the experimental building

The design of the experimental building included the use of a specific straw type and new detailing designs. The raw material of the bales was rice straw. The advantages of using rice straw was introduced in the Chapter 1. The rice straw was sourced from large bales produced by a New Holland Baler on the field and were re-baled in the factory. Dimensions of the bales were about 800mm (length) x 450mm (width) x 350mm (height).

The experimental building was a single story bungalow with pitched roof (Figure 3.10).The layout of the building was similar to the existing residential building in rural area in northern China. Because the straw bales are not official building material in China, the experimental building were not a load-bearing straw bale building. The structural frames and foundation of the experimental building were made of cast concrete, being the construction technique with which the builders used in this project were familiar. For the same reason, the building was designed to have a cold roof, thus the insulation layer in the roof was laid beneath above the ceiling. The experimental building was constructed in an open field in the campus of Jilin Jianzhu University. The building was orientated on cardinal directions and there was no structure and obstruction around the building.

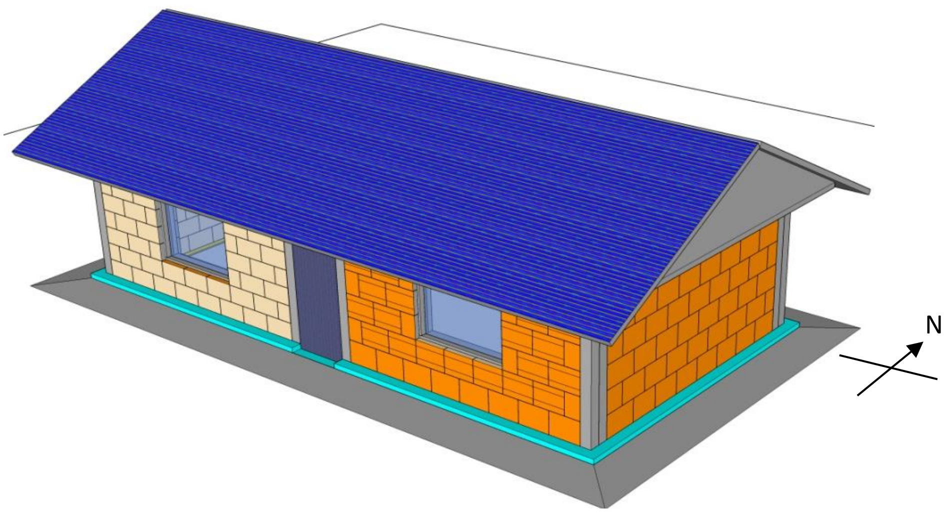


Figure 3.10. Perspective of the experimental building with laid flat straw bales (light yellow) and on edge straw bales (dark yellow).

There were two stacking methods in the experimental building to examine the effects of local climate on the straw bales. Chapter 2 reviewed two stacking methods of straw bales in construction of straw bale building. The west flank of the building had stacking of laid-flat straw bales and the on edge bales were used in the east flank (Figure 3.10 & Figure 3.11). Comparing with the laid flat straw bale walls, the laid on-edge walls have one less level of bales. To minimise thermal bridging of the concrete structure, EPS insulation boards were used between the concrete frames and between straw bales and frame in the east gable wall and the west gable wall.

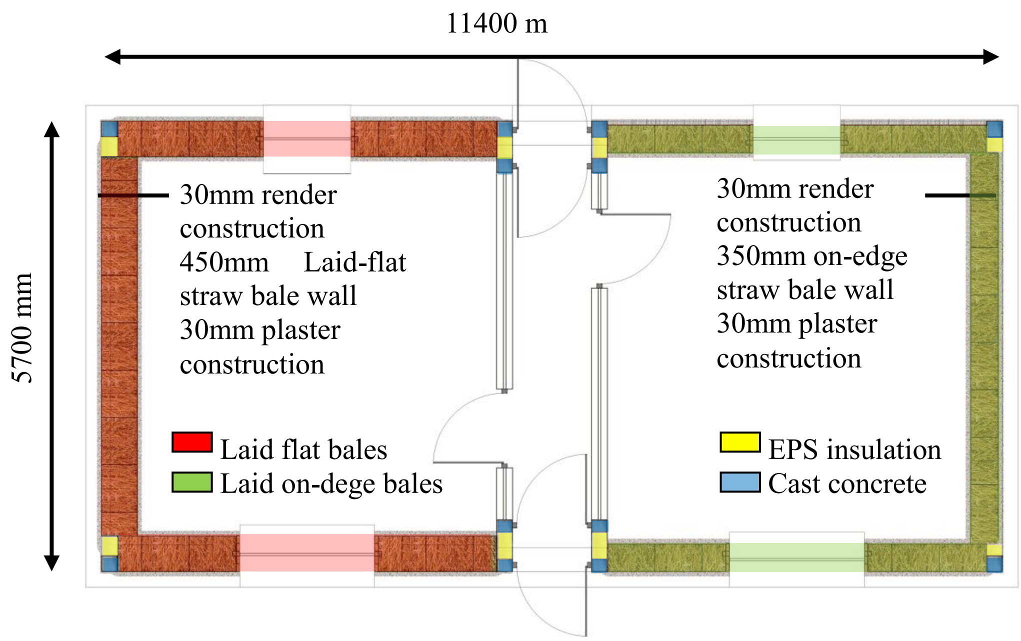


Figure 3.11. Floor plan and applied bale stacking.

The building was designed to have continuity of thermal insulation materials in order to avoid thermal bridging. The foundation of the experimental building was laid on continuously 200mm thick EPS board (Figure 3.12). The insulation layer of the roof had the same thickness. The design of the experimental building also featured double external doors. Required by the regulation (JGJ26-2010), the external door must be double door in the climatic area of Changchun (JGJ26-2010, 2010). The double doors were installed with separate concrete frames with insulation material between the frames (Figure 3.12). Design U-value of all building elevations was less than 0.20 W/m²K and the windows and doors had U-value of 1.5 W/m²K (Table 3.2).

Table 3.2. Thermal insulation construction and design U-value of building envelope

Building element	Target U-value of designs	Insulation material	Thickness (mm)	Thermal conductivity
Roofing	≤0.20 W/m^{2}K	EPS insulation	200	0.036 W/mK (manufacture)
Laid-flat straw bale walls	≤0.18 W/m^{2}K	Laid-flat straw bale	450	0.065 W/mK (Shea *et al.*, 2013)
Laid-on edge straw bale walls	≤0.19 W/m^{2}K	On-edge straw bale	350	0.065 W/mK (Shea *et al.*, 2013)
Roofing	≤0.19 W/m^{2}K	EPS insulation	200	0.036 W/mK (manufacture)
Foundation	≤0.20 W/m^{2}K	EPS insulation	200	0.036 W/mK (manufacture)
Door	≤1.50 W/m^{2}K	Glass mineral wool	50	0.035 W/mK (manufacture)
Window	Overall ≤ 1.50 W/m^{2}K	Triple glazing (3mm glass and 10mm cavity) with 65mm thickness PVC frame		

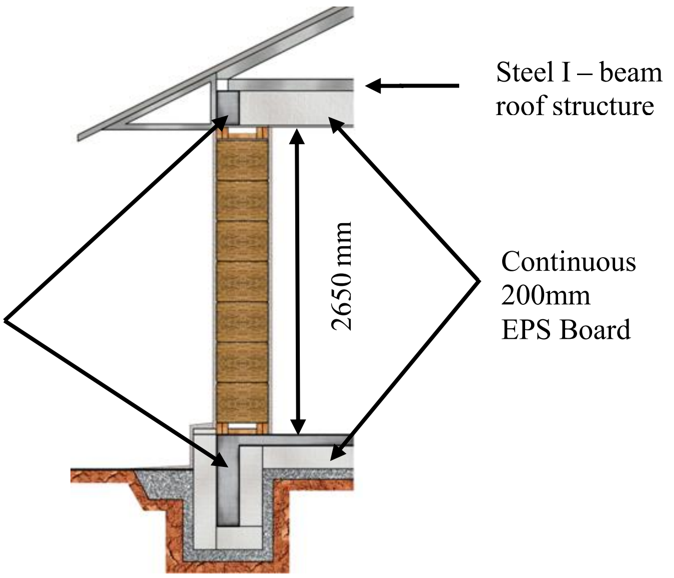


Figure 3.12. Flat laid bale wall construction of the experimental straw bale house.

3.3.3. Proposed construction detailing in the straw bale building

Compared with current construction methods described in section 2.1.3, there are three minor changes of the straw bale house include pinning system, redesign of toe-up knee walls of straw bale walls and using lime based rendering construction.

a. Pinning system

The experimental building introduced pinning system in the construction. The pinning system used pointed timber dowels to connect each bale. Connections between bales were used by Jones (2009) and Myhrman (1998) which were analysed in Chapter 2.

Figure 3.13 shows the pinning system developed in this research. There were three different types of pins in the straw bale walls in this research: long pin, short pin and rebar pin. Both long pins and short pins were made of timber and the rebar pins were customised steel rebar. The short pins were 200mm long which were shorter than the thickness of typical straw bales. The short pins were installed in the base plate and they were designed to fix the first layer of bales. The longitude of the long pin was 1m. The longitudes of the pines were more than two layers of bales and therefore they can connect two layers of bales. The rebar pins were designed to connect the straw bales and the concrete frames. The rebar pins were used horizontally to fix the bale walls to columns. The horizontally placed rebar pins were passed through preformed holes within the concrete columns. The horizontal rebar pins were design to increase buildability and stability of the bale walls during construction.

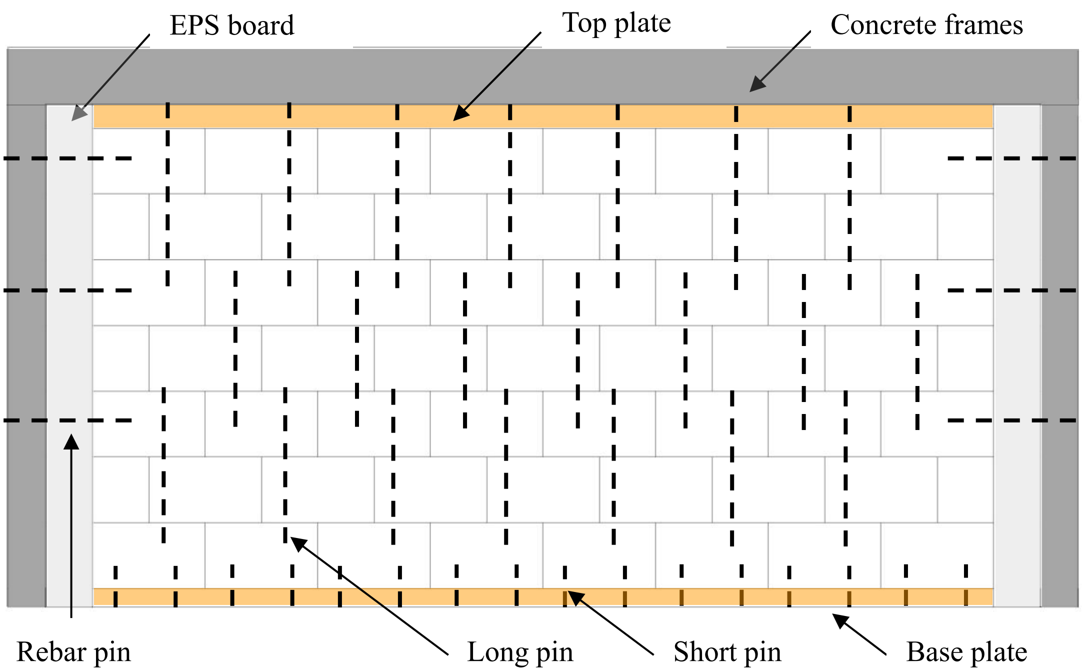


Figure 3.13. Pinning system of the experimental straw bale building.

b. Toe-up base plate

The toe-up construction used is a variation of the typical timber base plate structure which is designed by Jones (2009). The developed base plates in the experimental building contained 100mm x 50mm timber beam, timber noggin between the beams, timber stud pin and thermal insulation materials (Figure 3.14). The timber stud pins were used to replace hazel stud in the Jones's system as poor availability of hazel in northern China. Comparing with the hazel pins, the round surface timber pines cannot fix the bales with double pins and therefore two additional noggins in the base plate were drilled to contain four timber pins in each bale in the experimental building (Figure 3.15). The timber element also incorporated with window frames to connect the top plate and base plate (Figure 3.16). The timber beams were fixed to the concrete floor in the construction. Comparing to the brick toe-up in the existing straw bale buildings in northern China, the design of timber toe-up was easier for construction and it had better connect between the concrete floor and straw bales than the existing brick knee walls in the ADRA project introduced in section of 2.1.5.

Figure 3.14. Base plate in the experimental straw bale building.

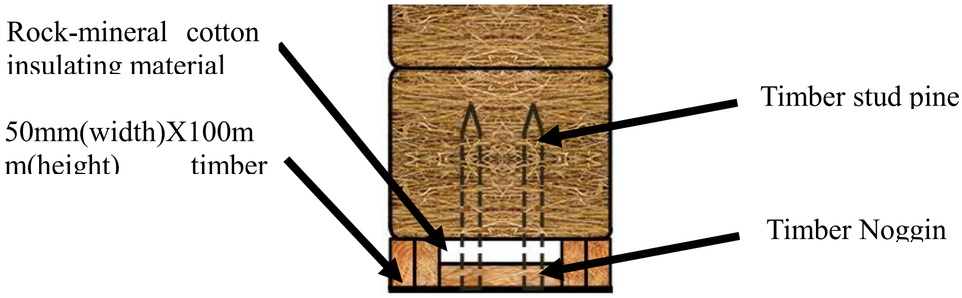


Figure 3.15. Section of developed base plate detail in the experimental straw bale house.

Figure 3.16. Wood work in the building design.

c. Render material selection

Non-hydraulic Lime render was applied in this project instead of cement based render systems commonly used in north China. The lime based render has been used in many projects in UK (Jones, 2009), US and Canada(Bergeron and Lacinski, 2000). In contrast with existing Chinese straw bale design, the experimental building included the first application of the lime render in north China. The render can provide breathability for straw bales within walls. Because there is no current application and understanding of using lime based render of straw bale buildings in northern China, the use of lime render might be problematic in dealing thermal shock issues.

A lime render construction was used in the research in Waterloo, Canada in where the winter months are similarly cold as the one in northern China (Bronsema, 2010). As no thermal shock issues were identified in the Canadian research (Bronsema, 2010), the issue was not expected to be a cause for concern in this research project. A first layer of the render was applied by hand to create solid bond between the lime plaster and the bales (Figure 3.17). Following this initial layer, metal mesh was applied across the whole surface to increase integrity and strength of lime render. In this research, the metal mesh was applied between first layer and second layer of the rendering to increase overall strength of lime rendering and maintaining solid boundary between lime render and straw bales at the same time.

A first layer of render is applied by hand to create solid bond between the lime plaster and the bales (Figure 3.18). Following this initial layer, metal mesh is applied across the whole surface to increase integrity and strength of lime render. The metal mesh is typically used in the render layer of existing buildings in northern China. However, the construction method is not recommended as it weakens the boundary between straw bales and rendering layer (Jones, 2009). Therefore in this research, the metal mesh is applied between first layer and second layer of the rendering to increase overall strength of lime rendering and maintaining solid boundary between lime render and straw bales at the same time.

Figure 3.17. Construction of first layer (left), second layer (middle) and third layer (right) of lime based render in the project.

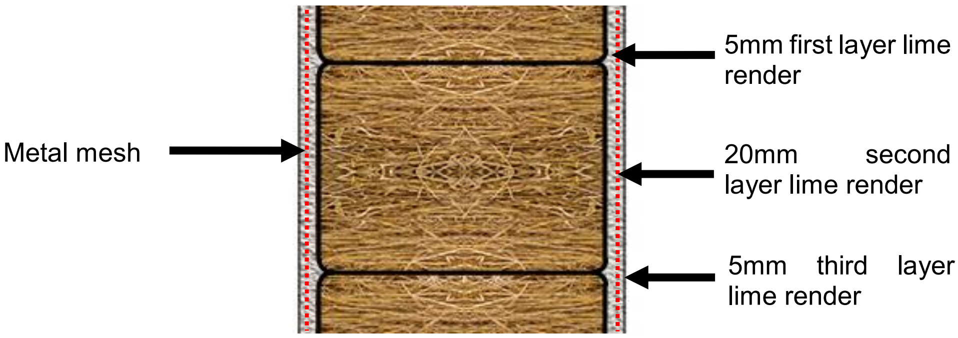


Figure 3.18. Section of straw bale wall in the project.

3.3.4. Set-up of long time monitoring

The monitoring devices were installed during the laying process of straw bales and they were programmed after completion of the construction phase. This section introduces the set-up of the monitoring research and the outcomes after the installation of the monitoring devices.

There are majority two methods of long term monitoring of straw bale walls. The wood stick method uses proper species of wood sensor to examine the moisture content of straw bales (Carfrae *et al.*, 2011). The wood stick sensor placed in the same environment as straw bales and the moisture content of wood stick is evaluated by electric resistance of the piece of wood (Carfrae *et al.*, 2011). A second method is to apply the adsorption isothermal models of straw (Lawrence *et al.*, 2009b). The straw bale walls can be evaluated by converting surrounding humidity levels of straw into moisture content of straw (Lawrence *et al.*, 2009b). Since this research focuses on both the conditions of hygrothermal environment and the moisture content of straw in the straw bale walls in the climatic conditions of northern China environment. The RH/T and isothermal model method are applied to provide direct data between straw bale walls and atmospheric environment.

To enable long term monitoring, hygrothermal sensors were embedded and used with data loggers (Figure 3.19). The data loggers were RHR300-W411 which were produced by the Dalian RHsens Technology Co., Ltd. Memory of the data logger was able to record 65536 data points. Battery life of the data logger was expected more than 1.5 years and powered up to two 5V sensors. The sensors were the TRH-100 Temperature & RH Probe and they were manufactured by the Pace Scientific. The sensors had accuracy of ±0.3℃ from -25℃ to 85℃ and ±1%RH@50% (±3% 0%-95%RH). The data logger recorded real time RH/T of sensors within straw bale walls hourly. The sensors were installed by the author during the construction and they were linked with the data logger after completion of the lime plaster layer.

Figure 3.19. Each set of monitoring device (two sensors and one data logger).

The Long term monitoring of the experimental straw bale building began after the construction was completed. The design duration of the monitoring research was 11 months and the first data acquired three days after the finish of the rendering construction. The placements of sensors were designed to monitor the most problematic areas for straw degradation in similar climatic regions in Japan (Holzhueter and Itonaga, 2014) and Canada (Bronsema, 2010). There were three different monitoring locations in the straw bale walls which were top positions, bottom positions and under window positions. The top locations were beneath the top most bales; the low locations and the under window locations were above the bottom most base bales (Figure 3.20). The under window locations were only installed on the south facing walls and north facing walls. Each monitoring location had two sensors in different depth in straw bale wall.

In each monitoring location, the sensors were placed 100mm depth inside the external surface and internal surface of straw bale walls. As there are two stacking method of straw bales involved in the experimental building, installation methods of sensors are different in the straw bales with the two stacking methods. The sensors were tied-up on the baling string in the laid flat straw bale walls (Figure 3.21). For the laid on-edge stacking of straw bale walls, the sensors were direct plugged into the bales.

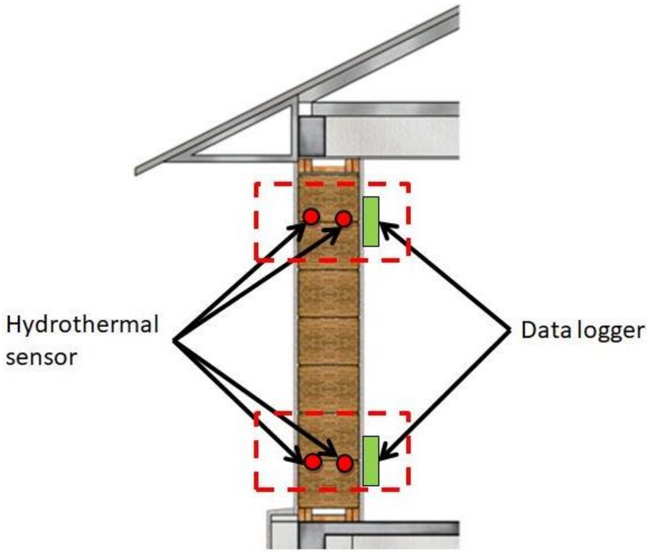


Figure 3.20. Monitoring locations through wall section.

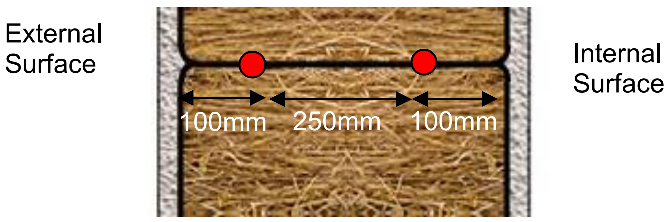


Figure 3.21. Sensors (red dots) of each location in straw bale walls.

There were total 20 monitoring locations in all straw bale walls of the building.

Monitoring locations were on each face of the building (Figure 3.22, Figure 3.23 and Figure 3.24). There were four locations in the east gable wall and the west gable wall. The total number and places of the monitoring locations were the same in the south facing walls and north facing walls with two bale stacking methods. Each monitoring location is named in Table 3.3.

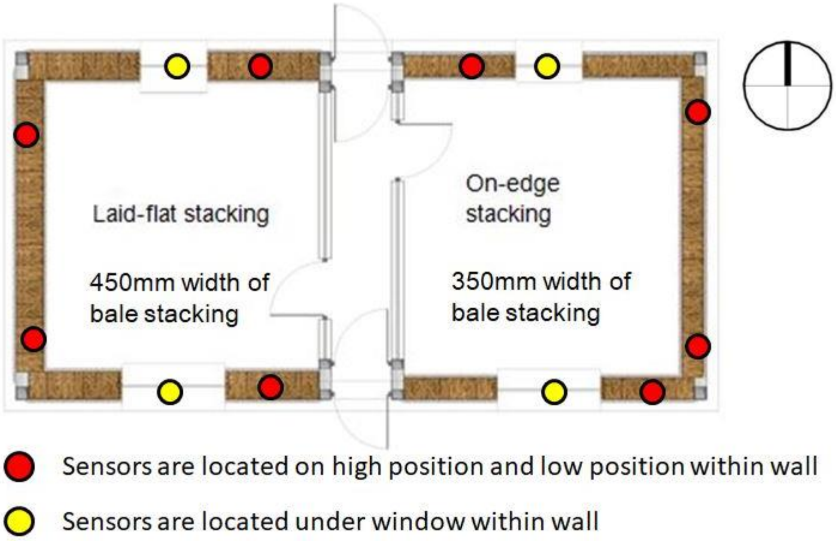


Figure 3.22. Monitoring locations within the straw bale walls.

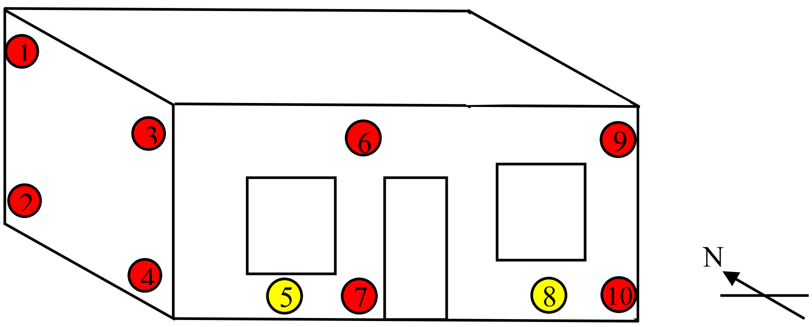


Figure 3.23. Monitoring locations inside the south facing walls and the west gable end wall.

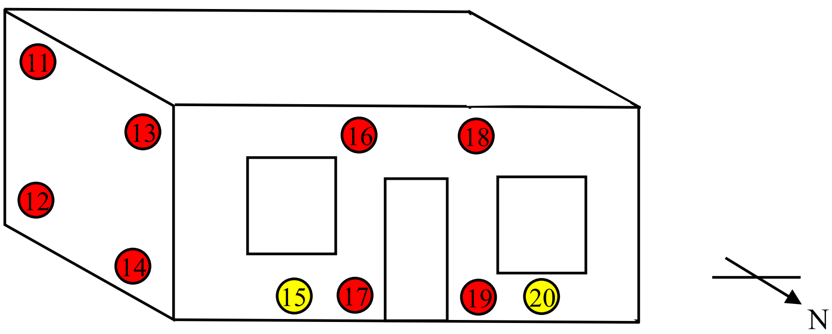


Figure 3.24. Monitoring locations inside the north facing walls and the east gable end wall.

Table 3.3. Number and location of each set of monitoring device in straw bale walls

Name of data logger	Position of data logger
1	450mm width of bale stacking, northern of west gable end wall, high position
2	450mm width of bale stacking, northern of west gable end wall, low position
3	450mm width of bale stacking, southern of west gable end wall, high position
4	450mm width of bale stacking, southern of west gable end wall, low position
5	450mm width of bale stacking, south façade, under window position
6	450mm width of bale stacking, south façade, high position
7	450mm width of bale stacking, south façade, low position
8	350mm width of bale stacking, south façade, under window
9	350mm width of bale stacking, south façade, high position
10	350mm width of bale stacking, south façade, low position
11	350mm width of bale stacking, southern of east gable end wall, high position
12	350mm width of bale stacking, southern of east gable end wall, high position
13	350mm width of bale stacking, northern of east gable end wall, high position
14	350mm width of bale stacking, northern of east gable end wall, low position
15	350mm width of bale stacking, north façade, under window
16	350mm width of bale stacking, north façade, high position
17	350mm width of bale stacking, north façade, low position
18	450mm width of bale stacking, north façade, high position
19	450mm width of bale stacking, north façade, low position
20	450mm width of bale stacking, north façade, under window position

3.5.5. On-site investigation of the experimental building

There are two phases of the onsite research on the experimental building in the justification of the straw degradation inside the walls of the experimental building.

The first onsite visit was in winter (16th January 2017 to 18th January 2017) after 6 months of the beginning of the monitoring research. During the first onsite visit the internal space was heated to examine the building for thermal bridges. The first site visit involved heating the building to 25℃ during the whole period of the site visit and taking infrared images to examine potential thermal bridging of the straw bale walls.

The final onsite visit was conducted direct after the end of the monitoring research (19th June 2017). During the second onsite research， lime render layer was opened up to check straw status within straw bale walls. Moisture contents of the straw within walls are measured directly using a HF-LM9 moisture content meter (Figure 3.25).

Figure 3.25. Moisture content meter in the final onsite visit in the research.

3.4. Summary

The first stage of the research was based on laboratory experiment. The physical characteristics of wheat straw and rice straw were examined through SEM. Both the DVS method and the desiccator method were applied in the following research of sorption properties of rice straw and wheat straw. To justify the susceptibility to degradation of straw bale construction in high humidity and high temperature environment, three specimens which replicated straw bale walling construction were placed in environmental chamber for 12 weeks.

In the second stage, the existing straw bale buildings in northern China were investigated and reviewed both through on-site visit of the buildings and analysis of the building detailing. There were two particular straw bale projects researched in the second stage: the straw bale building project in Jiamusi and the experimental straw bale building in Baishan. Investigations of the construction detailing and current status of the straw bale buildings were evaluated during the on-site visit of the buildings. Standard questions were also designed to outline the perception of local residents on the straw bale buildings.

Based on the understanding of straw and straw bale buildings in previous two stages, construction of an experimental straw bale building and the following in-site research of the building were conducted in the third stage. The experimental building was supported by Jilin Jianzhu University and it was constructed in Changchun, Jilin Province. The building incorporated pinning to stabilize straw bales during stacking process of bales, toe-up plate to reduce susceptibility to moisture damage of straw bale walls and application lime render to ensure breathability of the walling construction. The following monitoring research contained 20 monitoring locations to evaluate the hygrothermal environment of straw bale walls of the experimental building through 11 months. Each location involved two sensor position of RH/T sensor and one data logger connected the two sensors. The research on the experimental building also included two investigations of the experimental. The first onsite visit was done in winter and the second site visit was conducted at the end of the monitoring research. Straw status was visually checked during both the site visits. Walling construction of the experimental building was drilled and opened during the second site visit to evaluate degradation potential of straw bales during the monitoring period.

4. Properties of straw as a building material

This chapter presents the experimental results of moisture adsorption properties of both rice straw and wheat straw. By understanding the adsorption properties of rice straw and wheat straw, modified isothermal model are proposed based on the experimental results. The following results aid in the evaluation of straw degradation risks of the two straw species inside straw bale walls in high temperature and high humidity environment. The results of the degradation research help to understand the suitability of existing degradation isopleth of straw in the environment inside straw bale walls. The suitability of the modified model and existing isopleth model will be discussed and analysed in the Chapter 7.

4.1. Sorption isotherm research

This section discusses the experimental results of the adsorption properties of rice and wheat straw. The first part of this section presents the results of the different physical characteristics of rice straw and wheat straw. The following part outlines the isotherm of the two straw species. The effects of the test method adopted and the effect of end capping are then discussed separately.

4.1.1. Physical Characteristics

The cross-section of wheat straw and rice straw are presented in Figure 4.1 and Figure 4.2 at a similar magnification. It can be observed that wheat straw contains larger cells compared to the rice straw. The cellular diameter of wheat straw continuously reduces as it progresses from the core towards the external surface (epidermis). However, the convoluted structure of the rice straw contains cells with less variability in size. The cellular size of rice straw has a similar diameter to the smallest cells of wheat straw (approximately 5-10μm). Wheat straw and rice straw both incorporate vascular bundles containing phloem and xylem cells although the size of these bundles in the wheat straw is significantly larger than in the rice straw. The bundle sizes are labelled in red ovals in Figure 4.1 and Figure 4.2. The differences in tissue density and cell sizes between wheat straw and rice straw may lead to different vapour sorption properties for the two species of straw at high humidity levels.

Differences between wheat straw (Figure 4.3) and rice straw (Figure 4.4) have also been identified on external surfaces in the SEM images. Unlike the visibly smooth surface of wheat straw, rice straw possesses spikes. The size of each spike is approximately 10-20 μm with the pointed ends oriented parallel to the straw stem (Figure 4.5).

The spiked features do not cover the entire external surface of rice straw, and are therefore not expected to have any significant impact on the moisture sorption properties. The effect of the spikes on rice straw may enhance the mechanical properties of rice straw bales by providing interconnectivity and needs further study. It should be noted that anecdotally, Californian straw bale builders report that rice straw bales are more rigid than wheat straw bales (King, 2006), which could be explained by this surface phenomenon.

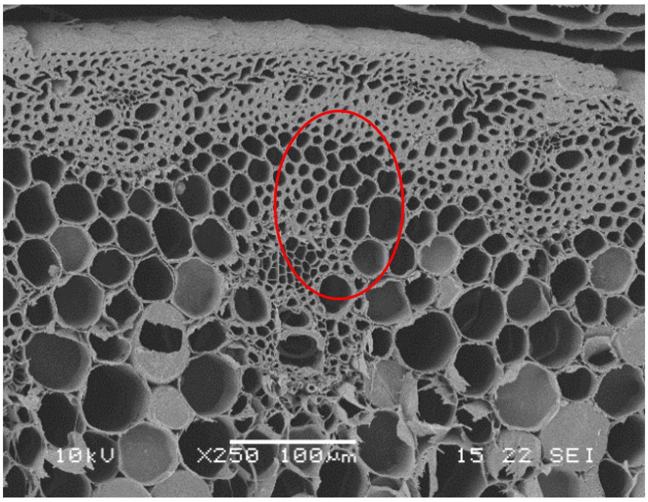


Figure 4.1. Cross-section of wheat straw.

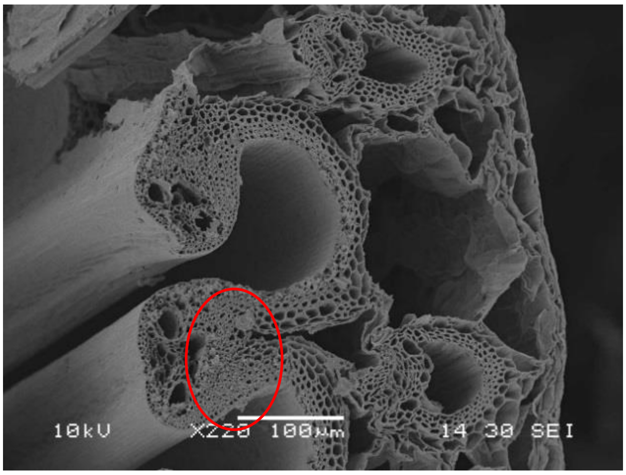


Figure 4.2. Cross-section of rice straw.

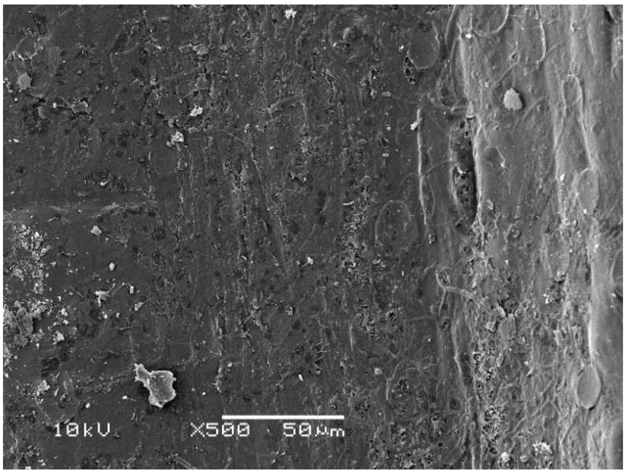


Figure 4.3. External surface of wheat straw.

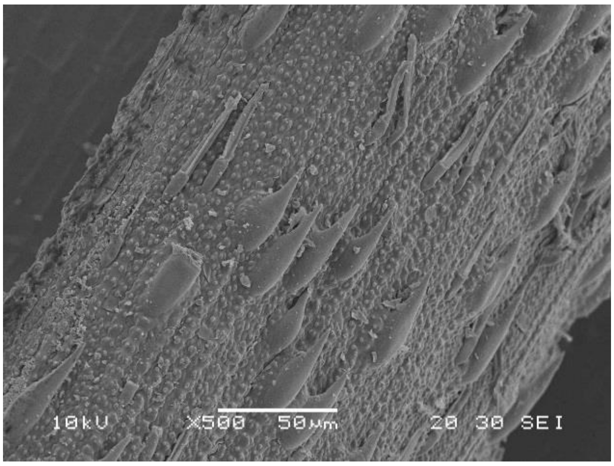


Figure 4.4. External surface of rice straw.

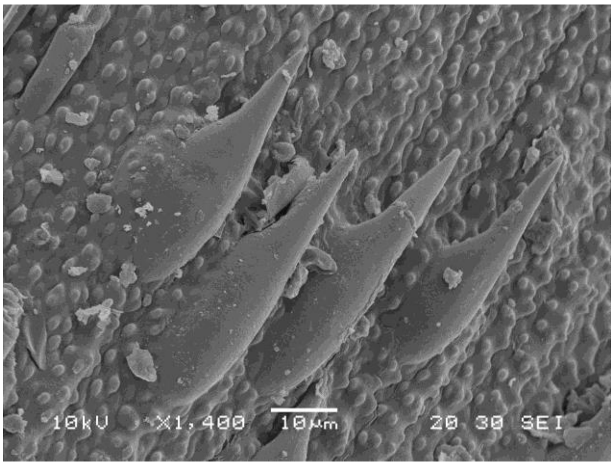


Figure 4.5. Spiked features on the external surface of rice straw.

4.1.2. Results of sorption isotherm

Despite significant differences in the cross-sections of the two straw species, the cellular structure has only a minor impact on the water sorption properties of each straw species (Figure 4.6). The moisture content of the two straw species shows less than 1% difference in the RH range from 0% to 90%. The results of the desiccator method show around 3% more moisture content for wheat straw than for rice straw at each similar relative humidity. All data are presented in Table 4.1 to demonstrate the range of measurements between the three specimens.

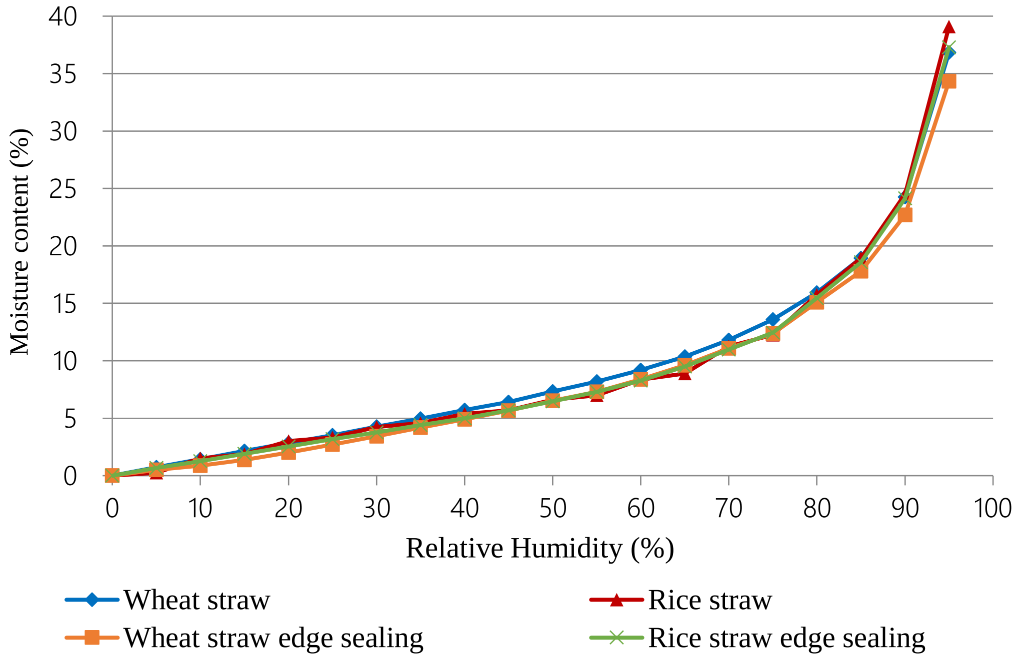


Figure 4.6. Sorption isotherm of untreated straw and edge capping straw

Table 4.1. Moisture content % of dry mass (MC) of wheat straw and rice straw in two saturated salt solutions.

RH Level	81.13% RH (ammonium sulphate)		97.42% RH (potassium sulphate)	
Straw Species	Rice Straw	Wheat straw	Rice straw	Wheat straw
Specimen 1	18.98%	20.26%	43.39%	48.99%
Specimen 2	13.69%	14.90%	38.47%	34.72%
Specimen 3	34.53%	22.94%	51.20%	56.07%
Mean MC	16.34	19.36%	46.59%	44.35%
Coefficient of Variation	22.0%*	21.0%	23.0%	14.0%

* Ignore specimen 3

There is no statistical difference between the isothermal sorption properties of the different types of straw based on the t-test. The peak moisture content of the two straw species have greater difference of moisture content at 95% RH (Table 4.2). The largest difference of moisture content between each sets is 4.8% in the DVS method. The result of the sorption isotherm study shows no significant difference between the water sorption properties of the two species in either the DVS method and the desiccator method.

Table 4.2. Moisture content % of dry mass (MC) of wheat straw and rice straw by DVS at high RH levels.

RH Level	80%		95%	
Straw Species	Rice Straw	Wheat straw	Rice straw	Wheat straw
Mean MC	15.73%	15.94%	39.08%	36.83%
Coefficient of Variation	2.0%	2.9%	1.3%	0.3%

a. Effect of test method

Both DVS method and desiccator methods achieved similar moisture content result for the two species of straw. The experimental results of the DVS method and desiccator method are not statistically different based on the t-test. Because the differences are small, they are likely to be associated with experimental error and with significantly different sizes and quantities of specimen and natural variations in the material.

The DVS method and desiccator method achieved variations of moisture content of the two straw species at different RH levels. There was a much greater variation of moisture content of the rice straw in the desiccator method than wheat straw following the desiccator method. There are two possible reasons for this. Firstly, differences in microstructure may affect the rate of adsorption of the two straw species. The irregular shaped bundles of cells of rice straw may be responsible for the larger variation of moisture adsorption of the rice straw specimens. Secondly, only 3 specimens of wheat straw and rice straw were used in each desiccator container. This limited number of specimens required by the standard might be fewer that needed to account for the structural variations that occur in natural materials.

Compared with the desiccator method, the DVS method produces data with much smaller variations. The moisture content variations are less than 2% in all relative humidity conditions for each adsorption isotherm experiment. The DVS method also features larger quantity of data in producing sorption isothermal model of the specimen. There are total 20 data points are collected in the DVS method comparing with 2 moisture content data of specimen in the desiccators method. Considering the advantages of the DVS method, this research analyses the data collected from the DVS method rather than the desiccator method in the following sections.

b. Effect of end capping

The open ended straw specimens showed larger variations of moisture content in the monolayer sorption and multi-layer sorption than the sealed end specimens (Figure 4.7). Open ended rice straw showed larger variation of moisture content than open ended wheat straw during multi-layer sorption from 50%RH to 70%RH. However, the larger variation was not observed in the sealed end straw. The sealed end cycles for rice straw and wheat straw showed significantly lower variation in monolayer sorption and multi-layer sorption. Below the fibre saturation point there was little difference seen between the two species, whilst above that point differences were more marked. The different cross sections of the straw species are likely to have an impact on water sorption properties of wheat straw and rice straw. During monolayer sorption and multi-layer sorption, access to the cut ends of the straw may be the reason for the variation in the water adsorption property of rice straw and wheat straw. Around the fibre saturation point, the cross section of the two straw species may have ability to minimise the variation in water sorption observed in the two straw species. Because the results were based on one sample of each straw species, further research will need to focus on a larger quantity of specimens.

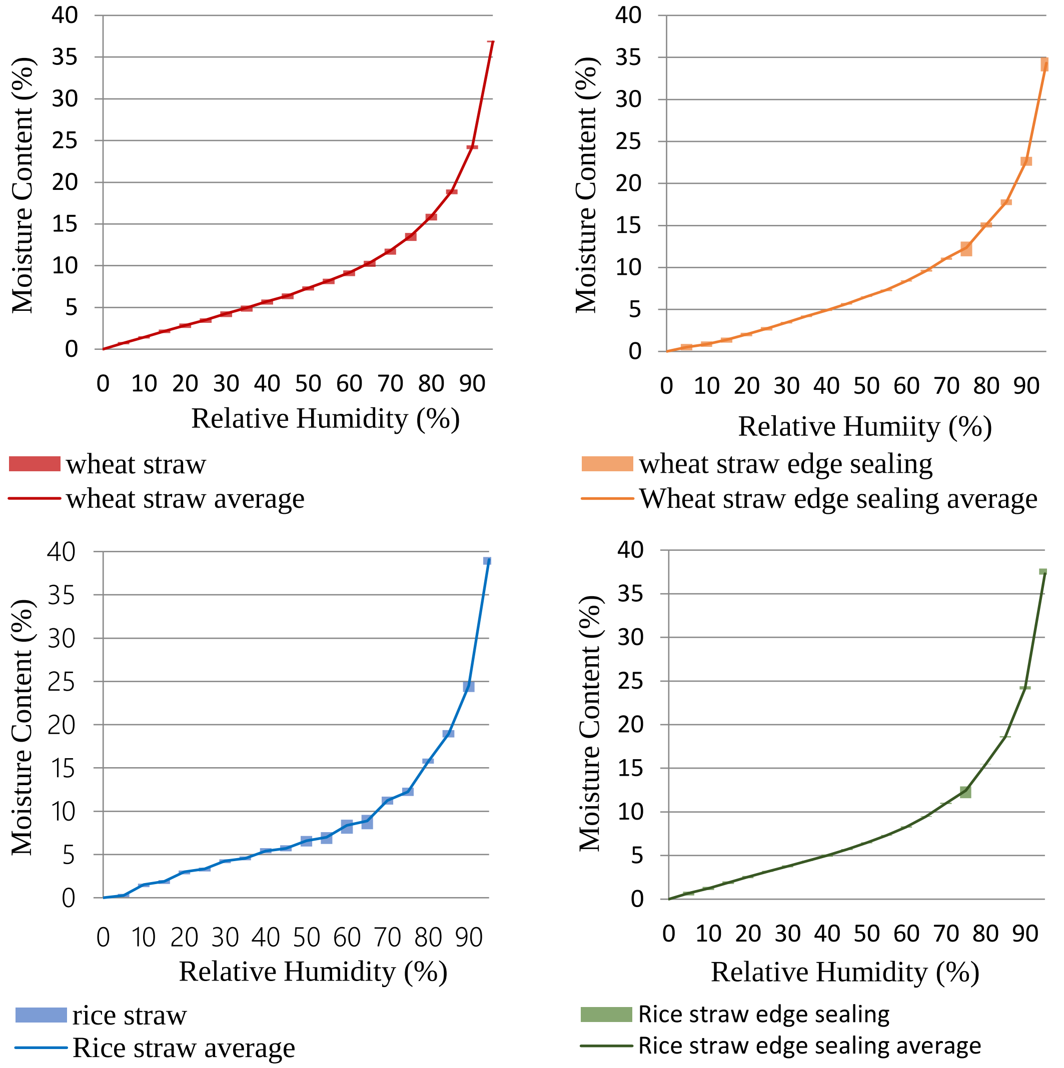


Figure 4.7. Moisture content variation of each specimen in each RH in DVS.

Although the ultimate moisture content of both open ended and sealed straw were found to be similar, the kinetics of adsorption were different. This is significant because in a real situations, air humidity levels fluctuate and moisture content of straw may not reach fully stability. As a result, true moisture adsorption/desorption will not be expected to map onto a model of moisture based on a stabilised sorption isotherm, and differences between sealed and open ended straw will be more marked.

Using the DVS method, RH increments are changed according to a set time period at high RH levels, and this does not allow full stability to be achieved (Figure 4.8). At 95% RH, the sealed end straw specimens showed a slower rate of mass change than the unsealed straw specimens at the beginning of the exposure. Both rice straw and wheat straw show slower response to RH change in the DVS method with sealed ends. However, because of the limited duration of time set, the specimens did not reach full saturation at the 95% RH level. At the final stages of exposure, dm/dt of the specimens was between 0.0036-0.0038 g/min which is greater than the set point for incremental change used by the DVS at humidity levels below 70% (0.002g/min).

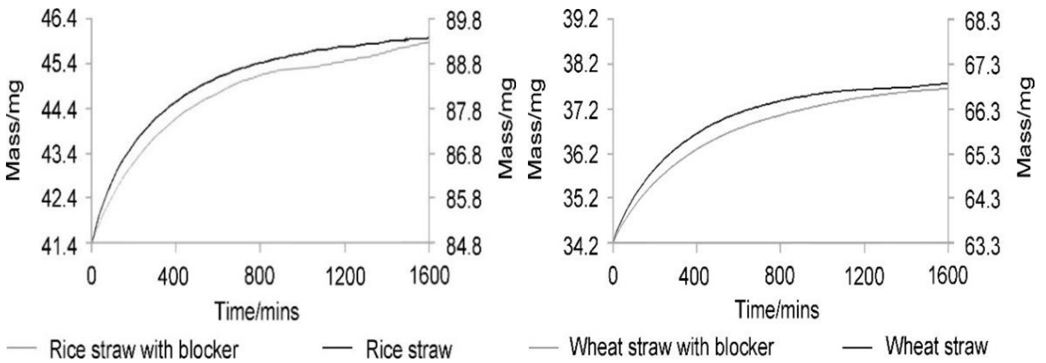


Figure 4.8. Mass change of rice straw (left) and wheat straw (right) in the 95% RH in the DVS method.

In the 5%RH to 65% RH range, this study used a dm/dt rate of below 0.002g/min as the set point for the achievement of equilibrium and to initiate a change in RH levels. The time taken to achieve equilibrium was similar for both rice straw and wheat straw at each set point. There were, however differences in the kinetics when comparing open ended straw with sealed end straw. On average it was found that over a full cycle of 0% RH to 65% RH, the open ended specimens achieved equilibrium 300 minutes (75% RH) more rapidly than the sealed ended specimens (Figure 4.9). This is assumed to be because access of humidity to the pores is only through one face of the stem wall for the sealed end specimens, whereas for the open ended specimens the pores can be accessed from both sides of the stem wall.

The results of the DVS method show that the open ended straw reach equilibrium quicker than the closed end straw in all RH levels The effect of open ended straw will likely depend on the relative ratio of exposed ends to the predominant surface area of the stem wall, and therefore the aspect ratio of the straw. The aspect ratio of the specimens in this investigation are not of typical in straw bale constructions and therefore the findings still need to be validated through further research on moisture movement of full scale straw bale walls. However, this finding may contribute to selection of the stacking method of straw bales in different climatic conditions, and modifying the makeup of a straw bale specifically for construction purposes.

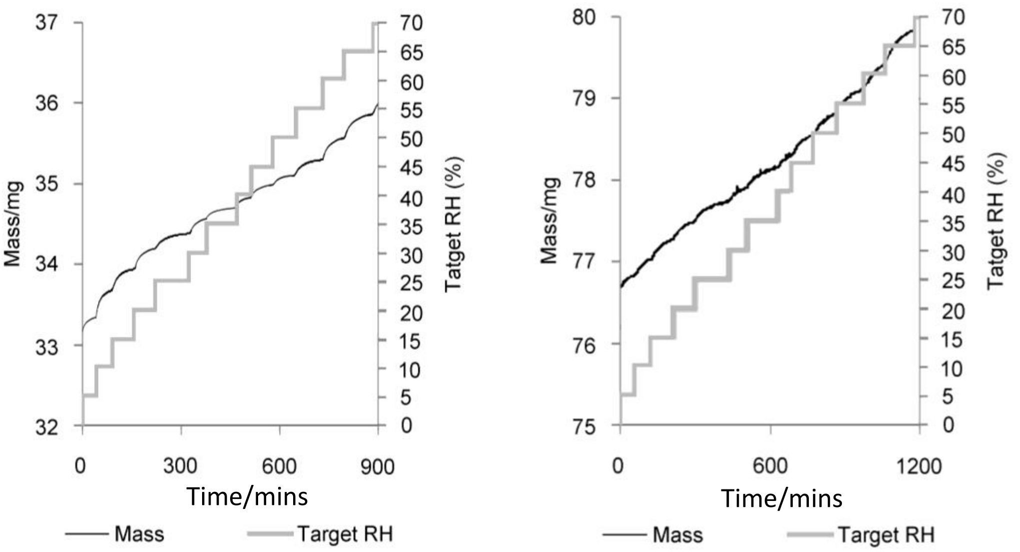


Figure 4.9. The dm/dt of Rice straw without end-capping (left) and Rice straw with end-capping in 0-65%RH (right)

c. Isotherm hysteresis of different specimen

The sorption and desorption isotherm of specimen are shown in Figure 4.10. The hysteresis of the specimen is greater with increasing RH levels in the DVS method. The peak hysteresis is in the 90% RH of all specimens. The hysteresis of wheat straw is higher than the rice straw in all RH levels in this research. The hysteresis of wheat straw is 1% to 2% higher moisture content than the hysteresis of rice straw in the RH levels from 30% to 90%. The raw material of straw bale buildings is rice straw over wheat straw for consideration of availability in northern China (Zhang, 2006). The use of the material may have benefits of low isothermal hysteresis between the sorption process and the desorption process of rice straw.

The hysteresis of rice straw shoe zig zag features in Figure 4.10. There are two explanations for this situation: Firstly, as the zig zag feature is observed in the sorption isotherm of rice straw (Figure 4.7), the feature could be the effect of a systematic error. Secondly, considering the different structure of cutting end of wheat straw and rice straw, the convoluted structure of cutting end of the rice straw may have different desorption process in comparison with wheat straw and rice straw with end capping.

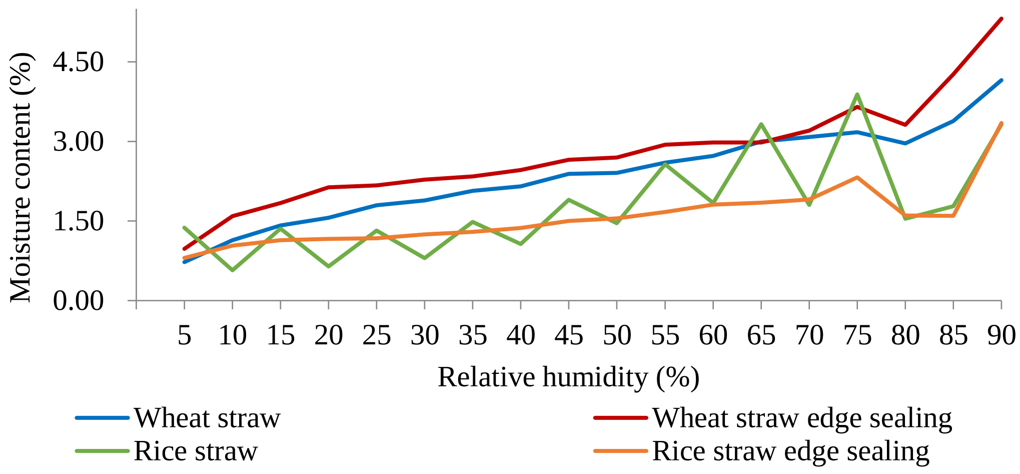


Figure 4.10. Average isotherm hysteresis of specimen in the DVS method.

4.2. Experimental results of degradation potential of straw bale

As the sorption process of straw is mainly through the cut end of straw which is identified in previous section, the perpendicular placing straw would have quicker water adsorption than the parallel placing straw in the experiment. The specimen with perpendicular placed straw would reach equilibrium quicker than the specimen of parallel placed straw. The specimens of perpendicular placed straw would experience longer period of time for potential degradation in the research. The degradation research simply the specimens to rice straw with two placing methods and one wheat straw with perpendicular placing method.

Due to the construction, the lime render introduces different amount of water in each specimen, the initial RH readings are different. As discussed in section 2.4.2, according to the degradation isopleth model of straw, the straw will not have notable degradation at the situation of 97% RH and 20℃. As soon as the initial RH readings are lower than 97% at 20℃, the different initial RH readings will not affect the research results. The initial RH readings of the specimens were 52% RH for the specimen with parallel placed rice straw, 77% for the specimen perpendicular placing of rice straw and 55% for the specimen with perpendicular placed wheat straw. The effects of the different humidity levels inside the specimen are effects of different adsorption process through external surface and cutting end of straw. The initial different RH levels justify that the straw bales with laid flat construction adsorb more moisture from the rendering construction than the laid on-edge bales during the same period of time. Detailed discussion and analysis of the effects of straw orientation on walling construction will be covered in Chapter 7.

Despite the notable difference of initial RH in the straw bundles, the specimens reach 95% RH relative in similar period of time in the climatic chamber. The specimens of perpendicular placing straw reached the environmental RH after 9 days and 12 days for rice straw and wheat straw respectively. The specimen of parallel placed rice straw has slightly longer time to reach 95% RH and the period of time is 15 days.

The visual checks of the specimens did not identify any recognisable straw degradation both in the experimental process and at the end of the experiments. Comparisons of the specimens of the straw status before experiment and after experiment are shown in Figure 4.11, Figure 4.12 and Figure 4.13. Existing research on sorption isotherm of straw have identified that straw would have serious degradation after more than 4 weeks exposure in the environment of 95% RH and 22℃ (Carfrae, 2011; Lawrence *et al.*, 2009b). The straw in typical lime rendered construction becomes protected.

Figure 4.11. Specimen of rice straw with parallel placing before the degradation research (left) and after 12 weeks in climatic chamber (right)

Figure 4.12. Specimen of rice straw with perpendicular placing before the degradation research (left) and after 12 weeks in climatic chamber (right)

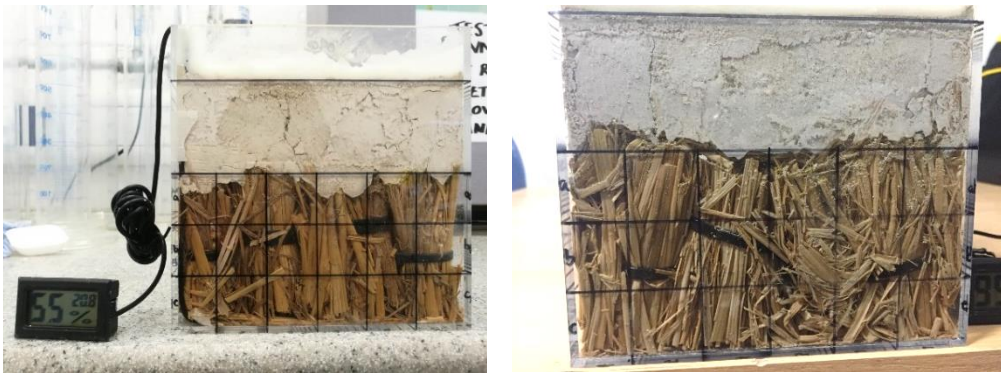


Figure 4.13. Specimen of wheat straw with perpendicular placing before the degradation research (left) and after 12 weeks in climatic chamber (right)

The experimental results show that straw does not exhibit signs of notable degradation in high humidity and high temperature environment. The property of low degradation potential of straw at high temperature has specific importance in building straw bale constructions in northern China. The potential self-builders of straw bale buildings are local farmers. Because of extensive farming activities in spring and autumn, the group of self-builders are available for construction activities merely in summer. Due to the low degradation of straw in high RH and high temperature environment in northern China, the straw bales in the buildings constructed in the summer months would have as little chance of degradation in other months in the northern China climate.

The reason for the lack of degradation maybe due to the effect of oxygen availability and presence of lime render. The lime rendering provides a sealed environment which can limit the fungi and bacteria activity in the form of anaerobic degradation (Summers *et al.*, 2003). The anaerobic activity of fungi and bacteria can have slow degradation effects on the straw bales. Available free moisture is a crucial factor on anaerobic activity of microorganisms inside straw bale walls (Clynes, 2009). The lime in the form of lime wash is widely used in preventing mould growth on walling surface in conventional buildings in China (Liu, 2015). The use of lime rendering on straw bale walls may prevent mould growth in the straw bale walls.

4.3. Summary

Two types of straw (rice straw and wheat straw) are initially characterised and rice straw is compared to wheat straw. The electron microscope has shown that there are notable micro-structural differences between wheat straw and rice straw. Sorption isotherm are subsequently presented that the physical differences between wheat straw and rice straw have a negligible impact on the equilibrium moisture content of the two straw species. Irrespective of straw species, water sorption characteristics of the two straw species is similar. Open ended straw equilibrates more rapidly with the environment than closed ended straw. The implication of this is that straw bales which have been trimmed to size (resulting in single strands of straw across the width of the bale) will equilibrate more rapidly than straw bales which consist of straw which has been folded at the edge of the bale. Bales made with cut ended straw will therefore have greater moisture buffering capacity than bales made with folded straw. In the long term, it would be expected that trimmed bales would therefore have less durability.

The experimental data acquired from the laboratory simulation of walling construction of straw bale walls show that the susceptibility to degradation of straw within straw bale walls is not significant at a high RH/T environment. The duration of the degradation experiment is longer than the summer months in northern China and therefore straw bales inside the experimental building would not be expected to suffer from notable degradation during the summer months. This will be validated by the monitoring research conducted on the experimental building. The results also show that the existing isopleth model may not produce reliable results for predicting straw degradation. The identified dangerous environment in the isopleth model is shown not to be accurate for predicting straw degradation when protected by a layer of lime render. The suitability of the isopleth model for predicting straw degradation will need to be discussed and analysed through a research programme of in-situ monitoring.

5. Results of building investigation of existing straw bale buildings

This chapter presents the results of the site visits to the two existing straw bale building projects in China. The outcome of each project is discussed through both a review of the design strategies used for each straw bale building and the results of site visits to the straw bale buildings. The ADRA project constructed straw bale buildings in a number of locations, and this research concentrates on one straw bale development. The project is located in Jiamusi, Heilongjiang Province and it was finished in 1999. The other design investigated is a steel frame straw bale farmhouse constructed as a single project for experimental purposes located in Baishan, Jilin Province. The farmhouse was innovated from the ADRA project and it was finished in 2010. The locations of the two sites are shown in Figure 5.1.

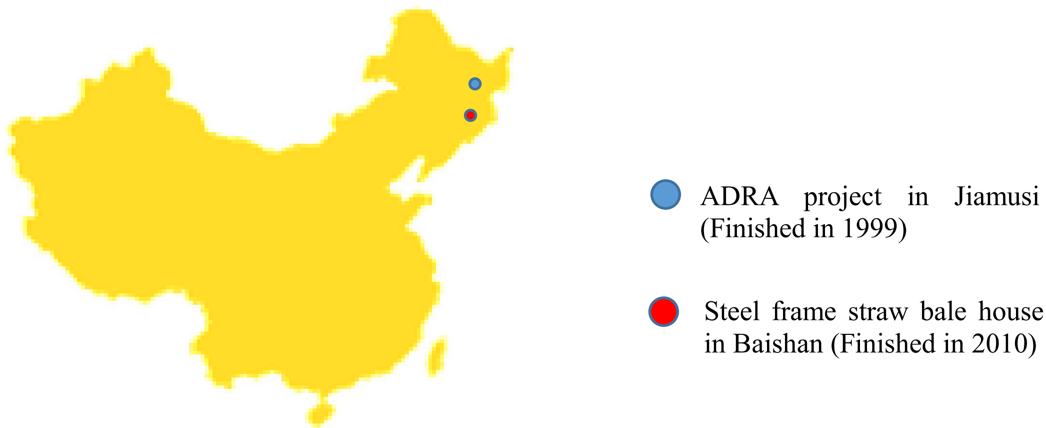


Figure 5.1. Area of the researched projects of straw bale building in China.

5.1. ADRA Project

The ADRA project in Jiamusi was the first development of straw bale buildings in northern China. This section begins with a discussion of the standard designs used to construct the straw bale buildings. As there are no published technical documents giving the construction detailing of the ADRA project in Jiamusi, the analysis of the ADRA project in Jiamusi is broadly based on the unpublished training manual produced to support the construction of the buildings in 1998 and the following published technical drawings of the construction detailing produced by Department of Construction of Heilongjiang Province (DCHP) in 2006.

A site visit was conducted to observe and record the condition of the buildings of the Jiamusi in January 2015. The building project in Jiamusi was part of the ADRA project and it was the first straw bale building community in northern China. There were total 32 houses constructed after the completion of the straw bale building project in Jiamusi (Figure 5.2). At the time of the site visit, the majority of the straw bale buildings had been either abandoned or demolished (Figure 5.3). As of 2015, a total of 11 straw bale buildings had been demolished and the land previously occupied by the buildings now occupied by two local factories. Among the demolished straw bale buildings, two of them have been replaced with masonry buildings. Thirteen of the original constructed straw bale buildings have been abandoned before the site visit. The majority of these had been left for more than a year and one of them had only been abandoned for 4 months previously. There were eight straw bale farmhouses that still occupied by residents at the time of the site visit. The site inspection foused on two particular straw bale farmhouses in Jiamusi.

The first house had been occupied by a local farmer since the completion of the building (House number 13) and the other uninhabited building (house number 25) had been abandoned 4 months before the on-site visit. As residents of five of the remaining straw bale houses were not at home during site visit, feedbacks from residents of the straw bale buildings were collected form 3 families who lived in the remaining straw bale houses.

Figure 5.2. Master plan of the straw bale buildings in the ADRA project in Jiamusi. (Google Maps, 2018)

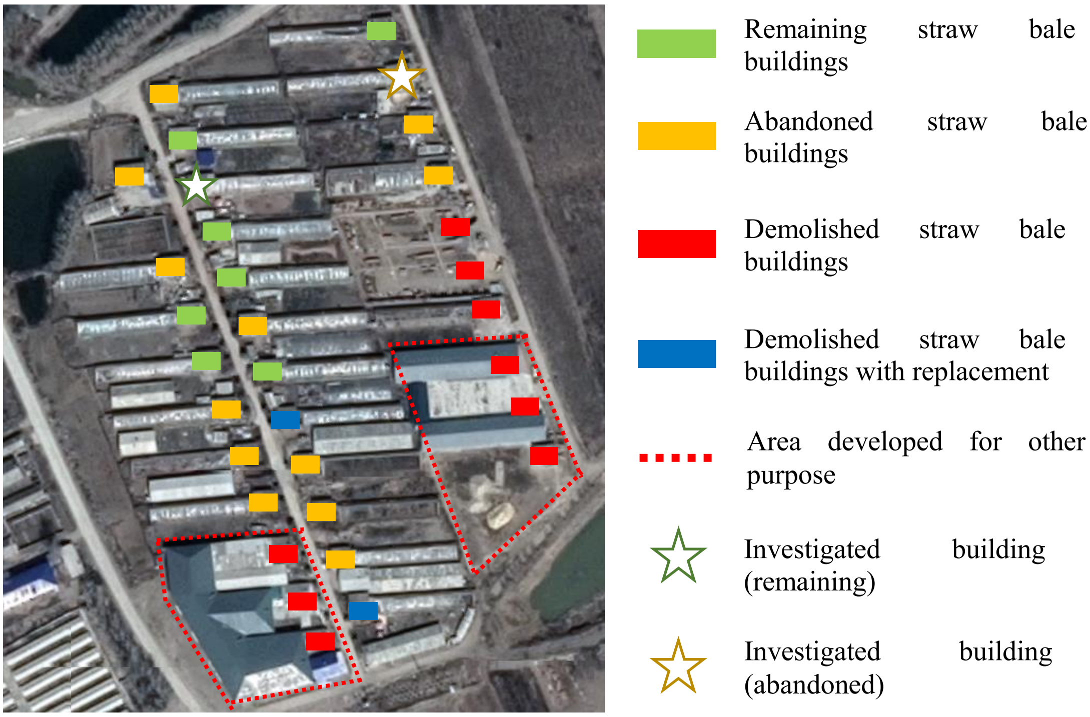


Figure 5.3. Current status of the straw bale buildings in the ADRA project in Jiamusi. (Google Maps, 2018)

5.1.1. Design strategies of the straw bale buildings

a. Bale selection

Wheat straw is recommended in the manual as being the most readily available raw material in the area of the ADRA project. As to the requirements for raw materials in the design manual, the straw should be completely dry or have a low moisture content (<17%) and have no grain or root contained within the straw. The bales used in construction are two string bales and the reference dimensions of the bales are 900mm (length) x460mm (width) x360mm (height). Because the in-fill construction method is used in the project, the requirement of bale density is not specifically mentioned. According to the illustrations in the manual, the construction bales should be ‘solid’. The DCHP standard uses similar requirement of straw bales. However, there are some changes of the initial training manual to adapt to real situations in the local area. Firstly, due to the rapid growth of rice farming in the Heilongjiang province, both wheat straw and rice straw are recommended in the standard ((DCHP), 2007). Secondly, due to various types of balers in the Heilongjiang province, the dimensions of bales are in a range of 700mm-900mm (length) x 450mm-500mm (width) x 340mm-360mm (height) rather than specified dimensions in the previous manual ((DCHP), 2007). The third change of the standard from the manual is the detailed requirement of bale densities in constructions. The bale lowest densities of dry basis straw bales should be over 80kg/m^3 in straw bale buildings ((DCHP), 2007).

b. Building design

The straw bale houses are in-fill straw bale construction. The load-bearing structure is a combination of masonry and concrete (Figure 5.4). The bricks support the vertical load of the buildings and the poured concrete beam serves as ring beams and lintels of windows and doors. Comparing the training manuals, there is no differences and modifications involved in the standard of straw bale building published by the DCHP.

Detail designs and connection of straw bale walls with other building elements are shown in the technical drawings collection ((DCHP), 2007). Major consideration of the foundation design is to keep straw bales from water damage. In the training material, foundations are required to be more than 200mm above ground level and must be higher than 30cm in rainy climate areas. As the buildings are constructed in cold climate regions, the foundations also should be laid lower than frost line. The detail designs of foundation include brick knell wall with vapour resistance layer on top, trench of coal cinder to drain moisture in straw bales (Figure 5.5) ((DCHP), 2007).

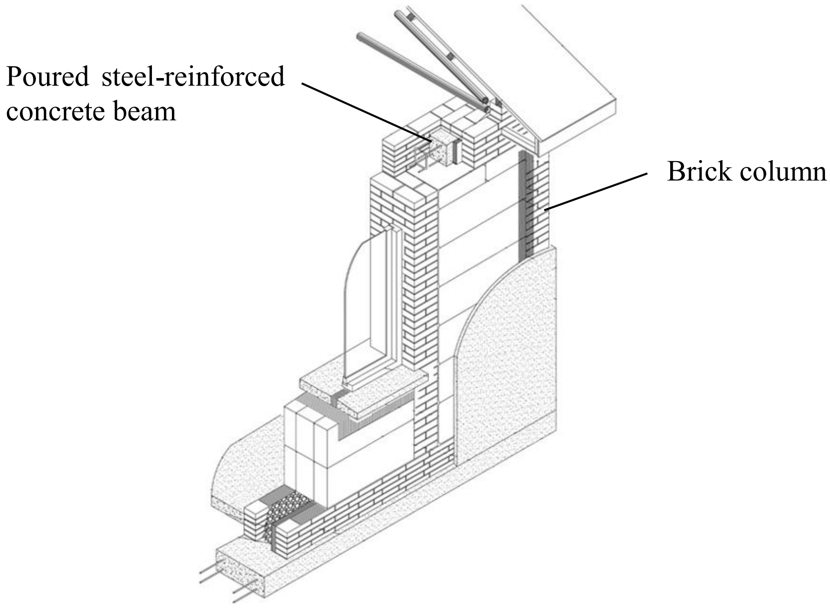


Figure 5.4. Typical structure of farmhouse in the ADRA project ((DCHP), 2007).

Figure 5.5. The foundation design of the straw bale house of ADRA project.

The walling design of the ADRA project and the standard of straw bale building is shown in Figure 5.6. Designs of straw bale walls also include the bale stacking methods and connection joints between straw bales and other building elements ((DCHP), 2007). According to the standard, bales should be stacked “flat” in straw bale walls (Figure 5.7). However, because in some locations the widths between brick columns are smaller than lengths of the straw bales, the straw bales should be vertically stacked in those areas ((DCHP), 2007). However, the folded side and cut side of bales should always face the render constructions of straw bale walls ((DCHP), 2007).

A metal mesh is applied all over the internal surface and external surface of straw bale walls in the ADRA project ((DCHP), 2007) instead of typically used pinning systems, found in straw bale buildings all over the world. The metal mesh is applied on the surface of straw bale walls and connects the brick columns and concrete beams ((DCHP), 2007).

To increase structural strength and integrity of straw bale walls in earthquake areas, the standard requires that cement rendering construction should be applied between each layer of bales ((DCHP), 2007). The construction is debatable for the use of gaps filling materials and the purpose of the construction. Thermal conductivity of cement is much greater than straw bales and the construction will decrease advantages of thermal insulation characteristics of straw bale walls. Filing gaps with an earth and straw mix is initially undertaken for the fire resistance consideration (Myhrman, 1998). The effectiveness of this construction detail is not certain.

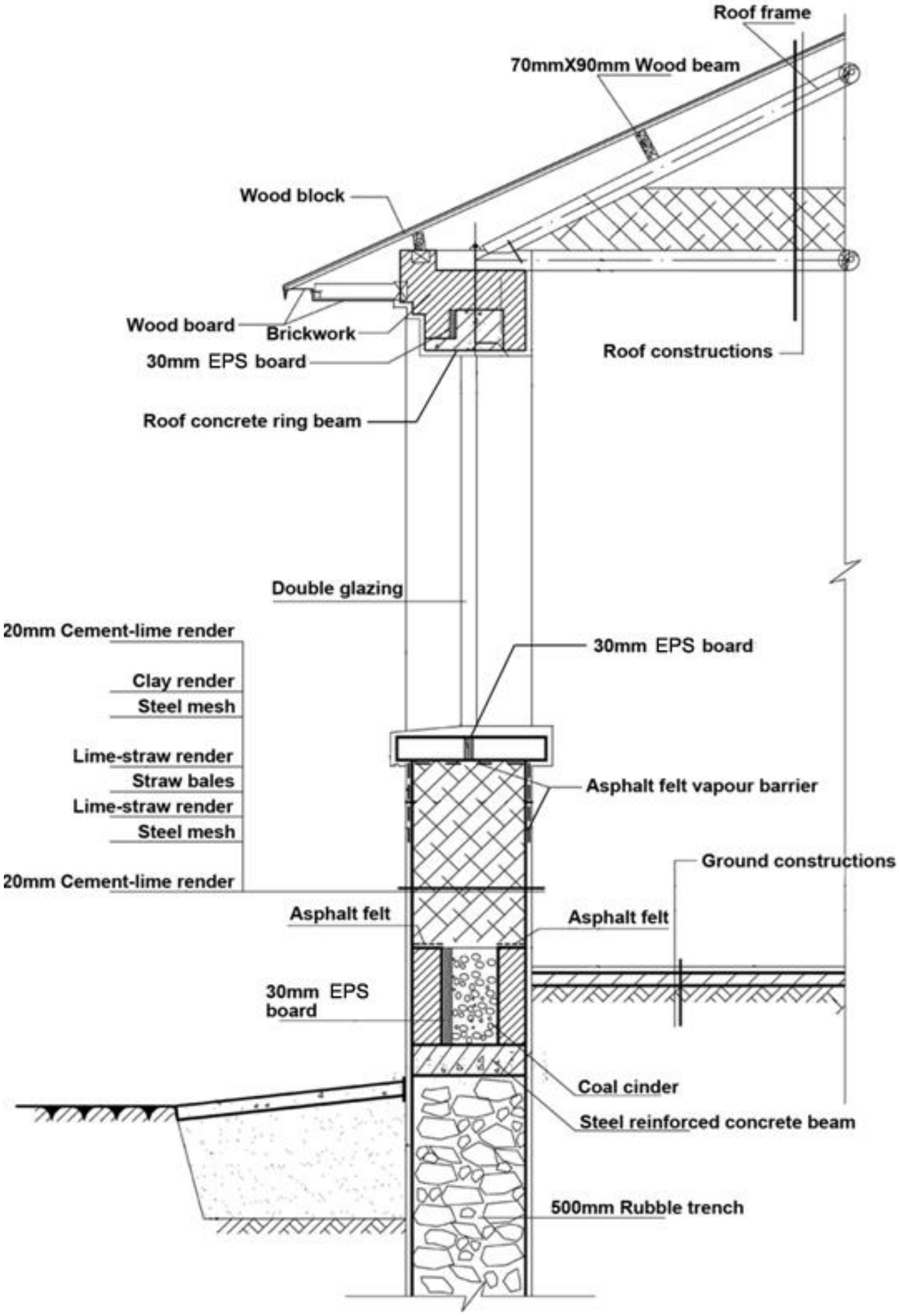


Figure 5.6. Reference foundation design of the foundations. ((DCHP), 2007)

Figure 5.7. Bale stacking of straw bale walls of ADRA project.

c. Render selections

The training manual and the standard provides several options of rendering constructions for the straw bales buildings in the ADRA project and in the Heilongjiang province. The typical rendering constructions are lime-straw render, clay render and cement-lime render. The lime-straw render consists of hydrated lime, sand and chopped straw. The composition ratio of the three materials by volume is 1:2-2.5:0.5. In the manual, an alternative to sand is brick powder or coal ash. If replacing sand with brick powder or coal ash, the ratio will be 1:1:0.5. For the clay render, the render material can achieved onsite and it is easy to work with straw bales. The clay render mix consists of clay and chopped straw. The ratio of these two materials by volume is 2:3. Adding one proportion of lime to the mix can increase the strength of the clay render. Cement-lime render is also proposed as an alternative in the construction. Good quality cement-lime render consists of one part of cement, one part of lime and 5-6 parts of sand.

Render application is also described both in the training manual and the standard, consisting of three layers of external render in the standard construction. First layer is recommended to be 10mm thick and it is applied directly to the straw bales. This layer will provide basic support of second layer and keep wall surface flat. Following the adhesive render layer, a second layer of render is applied at a thickness of 7.5mm-10mm and forms an integrated render layer of straw bale walls. The outside render layer is 5mm thick and it is designed to fill small cracks and for aesthetic purposes. The first two layers must be mixed either with hemp fibre, glass fibre or chopped straw. There is also a non-fibre construction illustrated in the training manual. On the first layer of the render metal mesh can be applied and fibres can be avoided in this construction. Metal mesh should be applied on the interface between straw bales and first render layer in both render construction.

5.1.2. Site visit of the ADRA project in Jiamusi

a. Building investigation of the remaining straw bale buildings

There are three major findings that came from the investigation of the two straw bale buildings in Jiamusi:

Firstly, condensation was found on the internal corner of the inhabited straw bale houses. Both signs of mould growth (Figure 5.8) and frost (Figure 5.9) on the inner surface of the gable end walls during the building investigation. The condensation issues indicate that there would likely be thermal bridging issues inside the walls which lead to surface temperature below the dew point. The surface temperature on the internal corner was lower than freezing point and the liquid condensation developed into frost during the visit (Figure 5.8). According to the owner of the farmhouse, the condensation is serious on the internal surface of gable end walls. The owner also reported that the frost appears from late December to early January when the lowest air temperature appears annually.

To reduce the identified thermal bridging issues, the residents of the investigated house built a sunroom extension outside the north facing walls 2 years before the onsite visit (Figure 5.10). The residents of the straw bale farmhouse commented that the sunroom extension had a positive effect on the condensation issues and room temperatures increased by 2-3 °C during the coldest period of winter. However, as the extension is applied on north facing walls, the effects of the extension would be limited on the potential thermal bridging issues inside gable end walls.

Figure 5.8. Identified mould growth at the inner corner of south envelop and east gable end of the investigated straw bale house in Jiamusi.

Figure 5.9. Condensation at the inner corner of north envelope and west gable end of the investigated straw bale house in Jiamusi.

Figure 5.10. Sunroom extension outside north facing wall of the occupied straw bale house in Jiamusi.

A second finding from the investigation is the linear cracking on the external surface of gable end walls. The cracks are identified both on the inhabited house and the uninhabited house (Figure 5.11 and Figure 5.12). As cracks of the render layer provide moisture a direct route to travel into straw bale walls, the cracking issues on the rendering layer could be devastating for straw bale construction as discussed in section 2.1. The cracks on the straw bale walls are only identified on the gable end walls of the straw bale buildings and the cracks follow particular pattern on the surface of the walls.

It is important to appreciate the detailing of gable ends. Making use of the photograph which was taken in 2006, the construction beneath the external plaster can be appreciated (Figure 5.13). The construction of gable end is similar to the construction of non-opening area of south walls and north walls. The cracks were observed both on surface of brick frame of gable ends and between the structural frames and infill straw bale walls.

As the owner of the house indicated, the cracks were formed during the first winter after the completion of the construction in 2006. According to the local residents, the cracking issues can be identified on the majority of the straw bale buildings in the area. According to a conversations with the residents, the cracking issues were not deemed serious in the investigated straw bale building and the residents of the building ignored the presence of the issues. However, investigation of the abandoned straw bale building showed serious cracks all over the gable end. Because of the serious cracking issues, the owner of the uninhabited straw bale farmhouse decided to move out 4 months before the on-site visit.

Figure 5.11. Cracks around adjacent area (highlighted in red) of straw bales and brick frames on the west gable end wall of the resided straw bale building.

Figure 5.12. Cracks around adjacent area (highlighted in red) of straw bales and brick frames on the east gable end wall of the non-resided straw bale building.

Figure 5.13. Detailing beneath external rendering of gable end in the ADRA straw bale building project in Jiamusi. ((ADRA), 2006a)

Thirdly, the applied rendering construction of the straw bale buildings is not exactly the same as the published technical drawing by the DCHP and the application has resulted in a weakness of the render to resisting straw degradation inside straw bale walls.

The render construction of the straw bale walls was visually checked through drilling and opening of the rendering construction on the east gable end wall of the unoccupied straw bale building (Figure 5.14). Unlike the recommended rendering construction in the published technical drawing, the applied render contained two types of render material with clay render inside and cement (lime-cement) outside. The use of metal mesh is also not mentioned in the training manual and the published technical drawing in render construction of the unoccupied straw bale building. Rather than applying a metal mesh between the base layer and second layer of render, as recommended in the manual and the published technical drawing, the metal mesh was applied between straw bales and the base layer of render. The application method of metal mesh was wide spread in the straw bale construction in the US (King, 2006). However, due to direct connection between straw bales and render layer is crucial in increasing stability of straw bale walls, the construction technique is not applied in newly constructed straw bale buildings (Jones, 2009b).

Straw degradation was also visually identified by the drilling an opening on the gable end of the uninhabited house (Figure 5.14). Straw was seen to have changed colour behind the render layer. Due to low air temperature during the onsite visit, straw and moisture inside straw bales was frozen and had become a solid block. As ice was identified visually through the opening, straw degradation behind the render layer can be expected in warmer seasons when ice melts into liquid water.

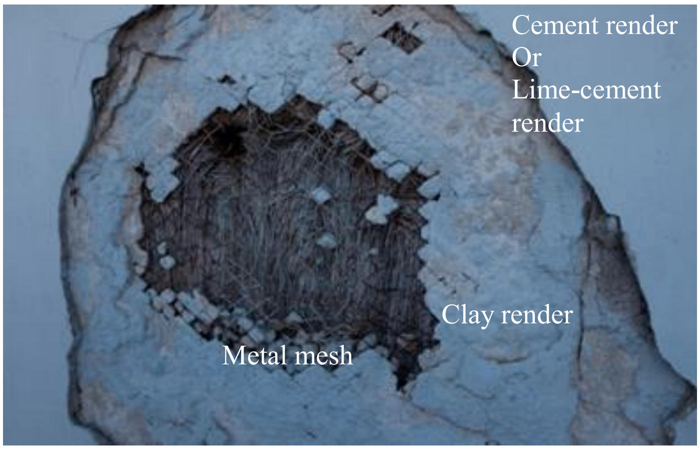


Figure 5.14. Layers of non-fibre reinforced render of straw bale wall in the unoccupied straw bale building in Jiamusi.

b. Feedback from residents of the remaining straw bale houses

All the three interviewed families of the straw bale buildings had lived in the straw bale houses since the competition of the buildings. The local residents covered a third of the total cost of the building, with the local government and the ADRA covering the rest. As a result, the residents payed around ¥ 6000-7000 (£660-770) for their new dwellings in comparison of ¥30,000 - 40,000 (£ 33,000-44,000) in local area in 2000. According to the feedbacks from local residents, there are three major findings:

Firstly, the manual was only available for the builder and volunteers involved in construction process of the straw bale buildings. The local residents have little knowledge of both constructing straw bale houses and maintenance their own straw bale houses. As a result, the local residents have little knowledge to maintain their house to a satisfactory standard. Even though all the residents have retrofitted their houses more than twice after completion of the buildings, they have never done any maintenance to the rendering. If local residents had sufficient understanding of the risks of cracks on the gable end walls of their house, the damage induced by the cracking issues could have been significantly reduced.

Secondly, even though the three families of the straw bale buildings give positive feedback on their straw bale houses in reducing their heating bills, the residents do not want to live in their straw bale houses any more. The condensation issues in their buildings make them worrying about the construction quality of their houses. Other than the identified issues, rumours and prejudice within the local community about straw bale buildings has had significant impact on the opinions of the residents of the straw bale buildings. According to the interviewed residents, local people think that straw bale buildings suffer from termite attack, and that cattle will break through the render layer and eat the straw inside the walls. In actual fact, due to the cold winter in the northern China, termite issues have never been reported as an issue for timber buildings in the area and it is highly unlikely that cattle will eat straw. The local people would also tend to think that the residents of the straw bale buildings must be poor to live a building built with straw.

Thirdly, the lifestyle of local people may make a significant contribution to the identified condensation issues in the building investigation. Due to the cold temperature in winter in Jiamusi, local residents tend to stay inside rather than outside. During this period, the building is well sealed to minimise infiltration and ventilation. As a result, the humidity levels inside the building constantly build up throughout the winter season. The high air humidity levels elevate the identified condensation issues identified during the building investigation.

Considering the low air temperature in winter and low air humidity in spring in northern China, the straw bale construction may have two advantages: Firstly, buildings require high thermal resistance during the low winter temperatures in the area. One significant advantage which can be provided by straw bale construction is high thermal resistance. The typical U-value of straw bale walling is between 0.14 W/m^2 to

0.19 W/m^2 (King, 2006). In comparison of the design standard of U-value of walling in the area, the straw bale buildings are 100%-300% better. Secondly, the feature of local climate is dry in the spring and winter. The monthly relative humidity levels are below 50% in April and May. The extreme low temperature is the reason of high level of RH in winter months. The feature of local climate can help to reduce the susceptibility of the construction system to decay. In Japan, in areas with similar climatic conditions, safe guidelines for straw bale construction specify a maximum of 80% relative humidity. According to the climate data (Holzhueter and Itonaga, 2010), straw bale construction in the typical northern China climate will not be exposed to conditions which will encourage decay and decomposition.

During the construction of the straw bale buildings in the ADRA project, majority of the people worked onsite are self-builders. As a result, the construction time was largely decided by the availability of local builders (Cao *et al.*, 2011). Considering most of the builders are local farmers who only have time in summer and winter, the construction process was from August to October for the ADRA project in Jiamusi (Cao *et al.*, 2011). However, the summer months are the monsoon season in the northern China and the on-site construction of straw bale buildings can be greatly affected by presence of rain (Jones, 2009). In the second, high air humidity levels in summer could lead to an extended drying period for straw bale buildings which are completed in summer. A combination of high temperature and high humidity levels in summer could lead to trapped moisture within the walls. The trapped moisture would be frozen in winter and liquefied in the following march. Potential presence of liquid moisture may lead to degradation of straw inside straw bale walls. As a result, the existing construction schedule in summer are not suitable for on-site constructions. As spring is a “dry season” in northern China, construction process between April and May would be suitable for further construction of straw bale buildings.

5.2. Steel frame straw bale farmhouse

The steel frame straw bale building was a research project at Jilin Jianzhu University to examine feasibilities of straw bale construction with steel structural frames. The straw bale building is located in a village near Baishan City, Jilin Province (Figure 5.15). The building project was completed by 2010 and all technical detailing was given in a peer reviewed paper (Cao *et al.*, 2010). Analysis of the construction detailing is based on this research paper

The experimental straw bale building is currently occupied by a local couple who built it. The couple have lived in the building since its completion in 2010 and They know well about the straw bale building they live in and they support application of straw bale constructions. The feedback about their straw bale building is rom a shortened version of the questions listed in Table 3.1.

Figure 5.15. Location of the experimental steel frame straw bale building.

5.2.1. Design strategies

a. Bale selections

Specifications of the straw bales are not given in the description of the farmhouse. Because the buildings are located near rice production areas in China, the straw in construction is rice straw. The quality controls of the bales in the research are referenced from the ADRA projects (Cao *et al.*, 2010). Bales in the project were produced on site using rice straw by a hand operated baler. The onsite production of bales allows for the dimensions of bales can be customised depending on the openings of walls (Cao *et al.*, 2010). Thicknesses of straw bale walls range from 200mm to 400mm (Cao *et al.*, 2010). Bearing in mind typical dimensions of bales in straw bale buildings, both the flat stacking method and the on-edge stacking method were applied in forming the in-fill straw bale walls in this project. As details of initial moisture content within bales were not stated in the work of Cao *et al.* (2010), there is some uncertainty as to the initial risks of degradation within the straw bales.

b. Building design

Designs of construction details include structural designs, floor detailing, roof detailing and straw bale wall design. The structure of the steel frame straw bale farmhouse was inspired by typical steel structural constructions in China (Cao *et al.*, 2010). In the study of Cao *et al.* (2010) steel I-beams and H-columns are used to construct the structural frame of the house (Figure 5.16). The floor construction also consists of steel I-beams, along with fireproof panels and metal decks (Cao *et al.*, 2010). The cross section of floor construction in the research of Cao *et al.* (2010) are shown in Figure 5.17.

Figure 5.16. Structure of partition walls and floor construction inside the house.

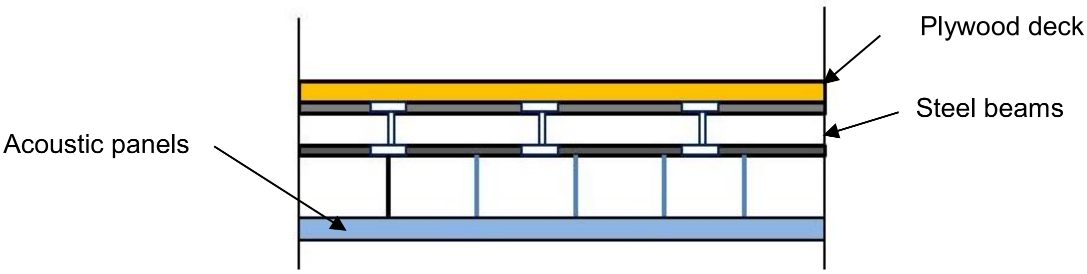


Figure 5.17. Floor detail design of the steel frame straw bale house. (reproduced from Cao *et al.* (2010)

The roof is a layered construction of structural steel with straw bale infilled (Figure 5.18). (Cao *et al.*, 2010). Straw bales are cut to be 200mm thick and covered by a layer of lime render (Cao *et al.*, 2010). Due to uncertainty of initial bale dimensions, straw orientation are uncertain in the roofing construction. Fireproof panels are installed on the back of straw bales and the fireproof panels and the I-beams of the roofing construction also contain the weight of the above layers of constructions (Cao *et al.*, 2010). Roofing tiles are used on the external layers and provide an extra layer of waterproof material and for aesthetic purpose.

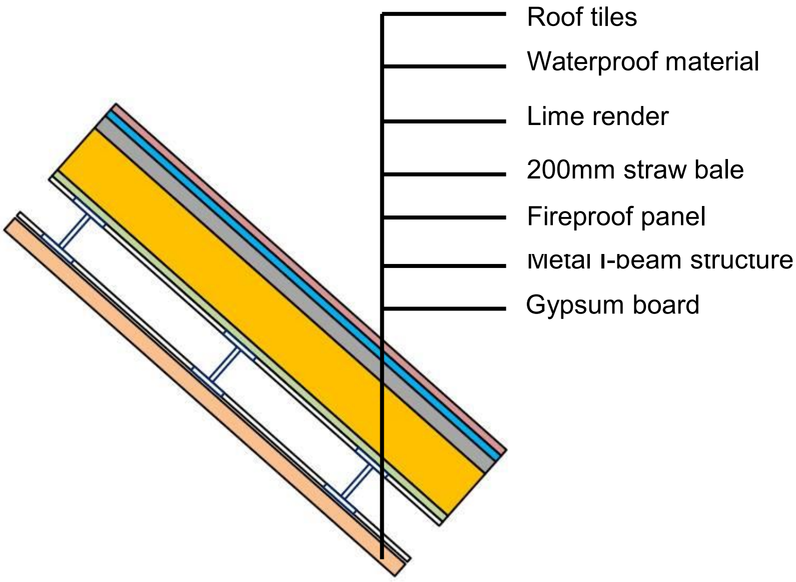


Figure 5.18. Roofing construction of the steel frame straw bale house. (reproduced from(Cao *et al.*, 2010).

The walling designs include in-fill straw bales, designs of openings, the internal render layer and the external render layer. Photos of the constructions which record the construction process present the detail designs of the openings (Figure 5.19).

Figure 5.19. Opening designs of the steel frame straw bale house.

c. Render selection

The render finish of the external surfaces consist of two layers of render mix, as shown in Figure 5.20. The first layer for the external finish is clay which is reinforced by chopped straw (Cao *et al.*, 2010). The second layer is cement plaster. Between the two layers, metal mesh is applied both on internal surface and external surface of the building (Cao *et al.*, 2010). The inner surface of straw bales also have two render layers. Clay render is used as the base layer and the gypsum render is the finish render layer (Cao *et al.*, 2010).

Figure 5.20. Layers of external finishes of the steel frame straw bale house.

5.2.2. Site visit of the infill straw bale farmhouse with steel frame

a. Building investigation

The site visit to the experimental steel frame straw bale house found three issues that may affect the durability of straw inside the walls:

Firstly, the walling construction of the surface of the washroom may lead to trapped moisture inside the straw bale walls (Figure 5.21). The inner surface of straw bale walls are covered with tiles inside the washroom. The purpose of the construction is to stop moisture damage to the walling construction. However, due to cement based render being applied on the external surface of the straw bale walls of the building, this will provide insufficient breathability to the straw bales. As trapped moisture issues may be formed inside the straw bale walls, the straw inside walls may have low durability with cement rendering both applied on inner surface and outer surface comparing to the straw rendered by the clay-gypsum on inner surface in this experimental building.

Figure 5.21. Tile applied on inner surface of straw bale walls inside washroom.

Secondly, linear cracks to internal corners of the walls are readily identified at all internal corners. The cracks are 1-2mm wide and straw can be seen behind the render layer of the inner surface (Figure 5.22). The identified cracks on the inner corner can be explained by the render construction of internal surface of straw bale walls. As described in 5.3.1, the clay base render and gypsum finish render are applied on the internal surface of straw bale walls. Such combination of render construction will result in soft and movable render layer of walls. As straw bales are not being solid in comparison with masonry walls, the straw bale around corners may provide insufficient support for the render layer. As a result, the linear cracks are formed around the inner corner of straw bale walls.

A visual check of the straw condition through the cracks showed that straw inside walls presented no notable colour change and there was no smell of mould growth around the cracks. However, as the house is currently occupied by residents, no drilling and opening process was possible to definitively assess the straw condition inside walls. However, as cracks provide direct pathway for moisture to travel into straw bales, they are potential risks to straw degradation.

Figure 5.22. Linear cracks on an internal corner of the straw bale walls.

The foundation design of the experimental building was also found to be inappropriate during the building investigation (Figure 5.23). During the onsite visit to the building, snow was observed to have accumulated outside the straw bale walls and the height of snow was at the same height as the building entrance. The high level of snow would not be problem during winter months, however, cares should be taken in spring months when temperature rises above freezing. The high level of snow will become liquid water and could penetrate into the straw bale walls. As a result, the design height of foundation should be much higher than the existing foundation. This issue was only identified in the experimental building, the straw bale buildings in the ADRA project in Jiamusi do not suffer the same issue.

Figure 5.23. Snow accumulation outside straw bale walls.

b. Feedback from the residents

Unlike the residents in the straw bale buildings in the ADRA project, the residents of the experimental steel frame straw bale building had a much deeper understanding of straw bale buildings.

The residents regularly maintain the external rendering layer on a two year basis. However, as the residents do not think the cracking issue are serious on the corner of the inner surface of straw bale walls, the cracks have been left since they were formed. According to the statement of the residents, the winter heating need for the building is significantly lower than a typical farmhouse in the area. The area of the experimental house is approximately twice times large as the typical farmhouse and the winter heating consumptions of coal are 30% lower than the typical farmhouse in the area. However, after investigation of the local farmhouse, the author noticed notably lower room temperature of the experimental house than local farmhouses. The room temperature of the experimental house was 16°C - 18°C whereas the temperature was 18°C - 22°C inside other farmhouses in the area.

The residents share a similar lifestyle with the interviewed residents of the straw bale buildings in Jiamusi. During winter months, the house is well sealed to stop uncontrolled ventilation and infiltration through gaps of the building. However, as the residents tend to spend their day time in their friend’s house, the experimental building is not occupied daily for as long period as the investigated occupied straw bale building in Jiamusi. The experimental building is regularly occupied by the residents for 10-12 hours during the night and the early morning.

5.3. Summary

The building investigations of existing straw bale buildings show how significant the impact of construction detailing is on the condition of the existing straw bale buildings in northern China. The condensation issues which are identified in the ADRA project are connected with potential thermal bridging inside the gable end walls. Due to inappropriate render formulation and application, cracking issues have been observed in the external render layer of the ADRA project in Jiamusi and the internal render layer of the experimental straw bale building in Baishan. The cracking issues have the potential to lead to serious degradation of straw bales inside the walls. The degradation has already been identified in the ADRA project in Jiamusi.

The straw bale buildings in the ADRA project account for the majority of straw bale construction in northern China and the straw bale building project has had a wide impact on both academic research and straw bale construction in China. As the steel frame straw bale construction was only a single project and there was no subsequent development of either the construction or the design, analysis of the construction techniques will focus on the ADRA project in Jiamusi in the chapter 7.

The perception of local residents towards straw bale buildings and lifestyle of the residents also have a notable impact on the straw bale buildings. Because there is little knowledge of straw bale buildings and infrequent maintenance of the render, many of the straw bale buildings have been abandoned and demolished. The condensation issues may be exacerbated by the lifestyle of the farmer in northern China. Other than the physical damage to the straw bale buildings, people’s prejudice against straw bale building may also limit further application of this type of construction in northern China.

6. Construction and monitoring of the experimental building

This chapter outlines the results relating to the experimental building. The outcomes of the construction process and set up of monitoring devices are discussed in the first sections. For the 11 months after completion of the experimental building, hygrothermal data of the monitoring locations was collected. The monitoring data were analysed and the hygrothermal data were converted to reflect absolute atmospheric water content at the various monitoring locations. Finally, the results of the post monitoring on-site visit to the experimental buildings are presented.

6.1. Outcome of construction of the experimental building

This section outlines the construction process of the experimental building. The outcomes of the construction process and the outcomes of the following monitoring device installation are discussed below.

6.1.1. Construction process of the Straw bale building

In contrast with the existing straw bale buildings described in Chapter 5, the on-site construction process of the experimental straw bale building involved two modifications. Taking account of the characteristics of local climate in northern China, it was considered that spring would be the most suitable period in which to undertake the construction process of the building. The construction period was planned to be from April to June to avoid construction taking place over the summer rainy season. Secondly, the experimental straw bale building was constructed by professional builders rather than employing self-builders as was done in the existing straw bale building projects.

Construction of the experimental began in middle April 2016 and finished in July 2016 (Table 6.1). The construction of the building began with a poured concrete slab foundation and steel reinforced concrete columns in the first three weeks. To increase overall thermal performance of the experimental building, EPS boards were installed as mould of the concrete slab foundation (Figure 6.1). Columns were constructed after the underground construction was finished. The final concrete slab provided a suitable storage area for the straw bales.

Figure 6.1. Timber model for casting concrete floor (left) and finish of the concrete beam of ground floor (right).

The designs of the experimental building indicated a requirement for a total 210 bales to complete the construction. Taking account of potential on-site damage to the bales, 250 bales were sourced from the local farmers. The bales were stored on site after completion of the concrete slab foundation. During the whole construction process, bales were raised up above the surface of concrete floor using timber battens to avoid potential moisture damage beneath the bales. To reduce hazard of rain during storing time, the bales were covered by tarpaulins during raining days and the water proof film was removed to dry out moisture inside the bale stacking during sunny days (Figure 6.2).

Figure 6.2. Installing Water proof cover (left) and drying bales during sunny day onsite (right).

The base plate and top plate were constructed during week 4 and week 6 (Figure 6.3). The work was designed to be finished within 2 weeks. However, for several reasons, the designed schedules were extended to 3 weeks. Firstly, because the carpenters on site were not familiar with the novel method; delays of the schedule were incurred. In addition, as the carpenters do not strictly follow the design drawings, many wrong distances were made between different pairs of timber noggins. As the distances of timber noggins were designed in consideration of bale length, all the inaccurate noggins have to be corrected and the correction process increase the delay of schedule for approximately one week. Thirdly, the construction process was also dragged back by unexpected earlier raining season than other years during the scheduled construction. The unexpected early coming raining season have significant impact on the construction process. As on-site carpentry work cannot carry on in rainy days, completion of base plate construction was severely delayed.

Figure 6.3. Finish of base plate and top plate.

Apart from the extended schedule of construction, the earlier rainy season also lead to significantly increased hazard of on-site damage of straw. Even though the straw bales were preserved under tarpaulins on-site during the construction process of the experimental building, there were still total 62 bales were damaged which account for roughly a quarter of the total bales. Since the bales onsite were not enough for the experimental building, 20 more bales were purchased in addition from the same source as the remaining bales.

Stacking of bales was conducted after finishing the base plate and top plate. As fixing the first layer of bales was crucial for overall stability of bale walls, the bales were tied–up at the end of each bale. The purpose of the construction technique is to fix the bales before applying lime rendering. However, the plastic string is considered to have an insignificant impact on the overall strength of straw bale walls after rendering has been applied to the walls. In total the laid flat construction consisted of 6 layers and laid on-edge construction had 7 layers. The process of bale stacking was also interrupted by the unusually early start of the rainy season. The straw bale walls were then pre-stressed by compressing the bales on all elevations in week 8 (Figure 6.4). The process used ratchet straps on top of the top plate and beneath base plate to compress the wall. The pre-compression increases density of straw bale walls and therefore limits subsequent creep in the completed structure. Construction of the ring beam used the top plates as a base for the formwork of the poured concrete. The construction method of the ring beam increases density of the bale walls further by applying additional compression and a good connection between the cast concrete and the top plate was also achieved by this construction method. Before rendering the straw bale walls, the straw bale walls were visually checked to identify any cavities or hollows between bales and any found were filled by stuffing small straw bundles into the identified cavity or hollow.

Figure 6.4. Finish of compression process (left) and finish of ring beam (right).

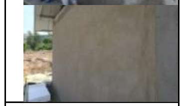
Assembly of the prefabricated roof structure, rendering of straw bale walls and other decorating work begin immediately after the initial curing of the concrete ring beam in week 8 and was finished in week 9. The straw bales were trimmed before plastering. Lime render was prepared onsite and was applied in three layers as per the design. 24 hours after the initial hand applied base layer, a second layer of lime render was applied. The metal mesh was fixed to the surface of both the first layer of lime render and the concrete frames. The method helped to reduce possible cracks within the lime render around the interface between straw bales and concrete frames (Figure 6.5). A final finishing layer of lime was applied after 24 hours and cured for another 12 hours.

Figure 6.5. Mesh layout (left) and finish (right) of second layer of lime render.

Due to the plasterers having little working experience with lime render, the application process of the three render layers involved many mistakes. As good connection between straw bales and lime render is critical for stability of straw bale walls, the first layer of render layer should penetrate into straw bales to create a good bonding with the bales. However, plasterers applied the first layer the same way as they would apply a render layer on masonry walls, and a quality check of the first render layer revealed that the bond between straw bales and the first render layer was not adequate. The plasterers' poor knowledge of lime render also contributed to customisation of the design requirements. During the application of the internal render to the west gable end walls, two plasterers mixed cement into lime render to increase workability of the rendering material. As a result, the whole inner render layer of west gable end wall had to be demolished and the plastering work redone. All the mistakes made by plasterers led to a 2 weeks delay to the overall construction schedule.

Table 6.1. Weekly Gant Chart (Week 1-6) of Construction of the Experimental Building

Week	Preparation work	Foundation and column	Wood work	bale stacking	RH sensor set up	Ring beam	Roof construction	Rendering	Decorating work
1									
2									
3									
4									
5									
6									
7									
8									

Week	Preparation work	Foundation and column	Wood work	bale stacking	RH sensor set up	Ring beam	Roof construction	Rendering	Decorating work
9									
10								 	
11									
12									

6.1.2. Outcomes of construction process

After the construction process of the experimental straw bale building, there were found to be a number of advantages and draw backs in the use of straw bale walls when compared with conventional masonry walls.

Firstly, the construction time of stacking straw bales was much less than laying bricks in conventional construction. The process of laying bales took one day in the building process of the experimental building. Total area of the walls was 80-90 m^2, and laying bricks for a similar size of building would have required 2-3 days. Another advantage of the straw bale building is the lighter weight of the bales than masonry bricks. A single bale can cover $0.3m^2$ to $0.4m^2$ area of walling. The weight of a single bale ranges from 16kg - 24kg in the construction process and a single builder can easily handle one bale. In comparison with a brick wall of the same surface area, the total weight would be 30kg – 40kg. Builders would need equipment to handle the bricks on the construction site.

Compared with traditional buildings in north China, the drawbacks of the modified construction included a lack of skilled workers and sensitivity to rainy weather. The construction involved the use of a lime-based render. As lime is not typically used in major construction projects in China, there are no skilled lime plasterers available to the work in the construction of the experimental building. Secondly, since onsite straw bale construction is sensitive to weather (King, 2006; Bergeron and Lacinski, 2000; Jones, 2009), the construction schedule was disrupted significantly by the unexpected early arrival of the rainy season in 2016. Because of the extensive rain from May 2016 to July 2017, many bales were damaged when they were in storage on the construction site and during the stacking process of straw bales. The bale damage issues show that the construction schedule of the ADRA project was also potentially problematic. Constructing straw bale buildings in summer months would lead to significant bale damage due to high temperatures and greater risks of rain damage in northern China.

6.1.3. Outcome of monitoring set-up

There are two major findings from the installation process of the monitoring devices:

Firstly, as the sensors were installed in the straw bales during the stacking process of the straw bales, positioning of the sensors was difficult in straw bales with on-edge stacking. Because the wires of the sensors were installed on the interface between each bale, adjustments to bale positions changed the sensor locations. As a result, the actual sensor positions could be different from the designed locations. There may not be notable changes to the design monitoring locations, however care should be taken in analysis of the monitoring data acquired at the sensor locations inside straw bale walls with on-edge stacking method.

Secondly, the initial RH readings were significantly higher than air humidity. As the straw bales were placed onsite more than 7 weeks before laying process of straw bale walls during the construction process, the hygrothermal environment within straw bales should have been similar to the atmospheric levels. The higher RH levels within straw bales are likely to have been caused by moisture present in the lime render whilst it was drying. Detailed analysis of the monitoring data is addressed in the following section:

6.2. Monitoring results

This section initially presents the yearly monitoring data acquired from the experimental building. The RH/T data at many monitoring locations presented high initial relative humidity as soon as the experimental building was completed. As a result, the presence of water inside straw bale walls and the drying trend of the walls is also discussed.

6.2.1. RH/T data

The monitoring data at the monitoring locations is discussed in this section. The analyses of the monitoring data involves an estimation of the accuracy of the sensor readings and an estimation of the actual water presence in the straw bale walls.

The data for all monitored locations were collected from 19th July 2016 to 19th June 2017. There were no data acquired from three positions: no data were recorded from positions No.3 and No.17 as the sensors were found to be faulty; the embedded sensors at No.2 position were never installed during the monitoring set-up. The full monitoring data of the monitoring positions are shown in Appendix A. To support the analysis of the relationship between the hygrothermal environment within straw bale walls and the atmospheric hygrothermal environment in the local area, climate data from 1st July 2016 to 30th June 2017 were provided by the Jilin Jianzhu University. The climate data of the local area included hourly air temperature, hourly air relative humidity and hourly air vapour pressure.

There was a short term heating process included within the period of the monitoring research. The temporary heating of the internal space of the building formed part of the degradation potential research which will be analysed in the following chapter. There were two separate heating instances of the internal space. The first heating process began at 20:00 16th January 2017 and ended at 3:00 17th January 2017. The target temperature of the heater was set at 25 ℃. The second heating process began at 20:00 23th January 2017 and ended up at 3:00 24th January 2017 with target temperature of 20℃. The temporary heating process had a notable impact on the monitoring results, as discussed in the following section. The temporary heating process for the degradation research had an influence on the temperature data of the monitoring positions from 16th January 2017 to 30th January 2017. The temperature significantly increased at the beginning of the heating process and dropped back to equilibrate with the surrounding temperature after 30th January 2017.

Monitored temperatures at all monitoring positions increased initially and peaked around two weeks after the monitoring began. The highest monitored temperature was 44.8℃ at the outer sensor of the No.5 monitoring location on 5th August 2016 (Figure 6.6). The monitored temperatures dropped below freezing point at the end of October. The temperatures of the monitoring positions stayed continuously below 0℃ from late November 2016 to early February 2017 during when the lowest monitored temperature was -14.7 ℃ at the monitoring location of No.19 in December 2016 and January 2017 (Figure 6.7). Monitoring temperatures later rose from early February and were above freezing point in early March at all monitoring positions. Unlike severe low temperatures inside straw bale walls in winter, the internal room temperatures were never recorded to be below 0℃ during weekly inspections of the building in the period of the monitoring research. Considering there was no regular heating system in the straw bale building in this research, the main reason would be the high thermal insulation properties of straw bale walls.

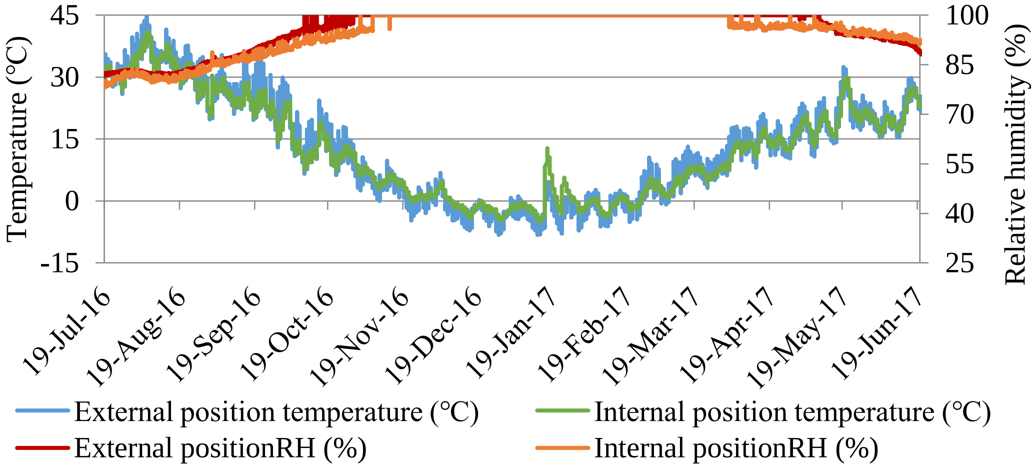


Figure 6.6. Monitoring data of relative humidity and temperature of the location No.5

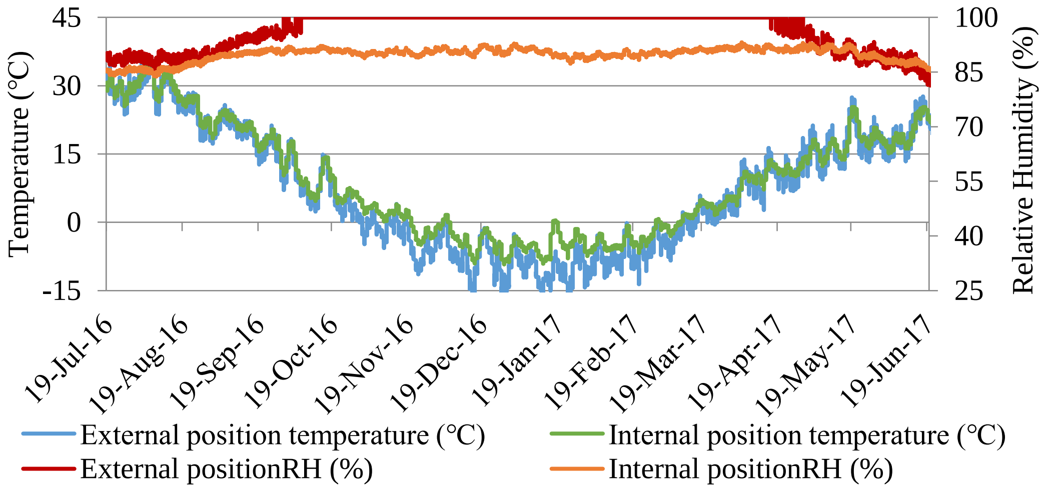


Figure 6.7. Monitoring data of relative humidity and temperature of the location No. 19

The temporary heating process had a notable influence on the RH/T data of the monitoring research. The impact was recorded between 17th January 2017 and 19th January 2017. Temperatures at all the monitoring positions were increased notably during that period of time. The increase of RH levels was synchronised with the RH decreases. However, the RH/T changes were found to be of a different degree in different monitoring locations.

Unlike the great change of temperatures in the monitoring locations, the RH levels range from 80% to 100% for most monitoring positions. The monitoring data showed high RH levels at the beginning of the monitoring period, but decreased in the first three weeks (Figure 6.8). As the decreases of humidity levels synchronised with the rise in temperature in all position, the lower RH levels in the monitoring positions may not indicate lower actual water presence in the straw bale walls. The RH levels continued to increase in the following months and ultimately reached 100% RH (Figure 6.7). The time taken for RH levels to reach 100% were different at all monitoring locations.

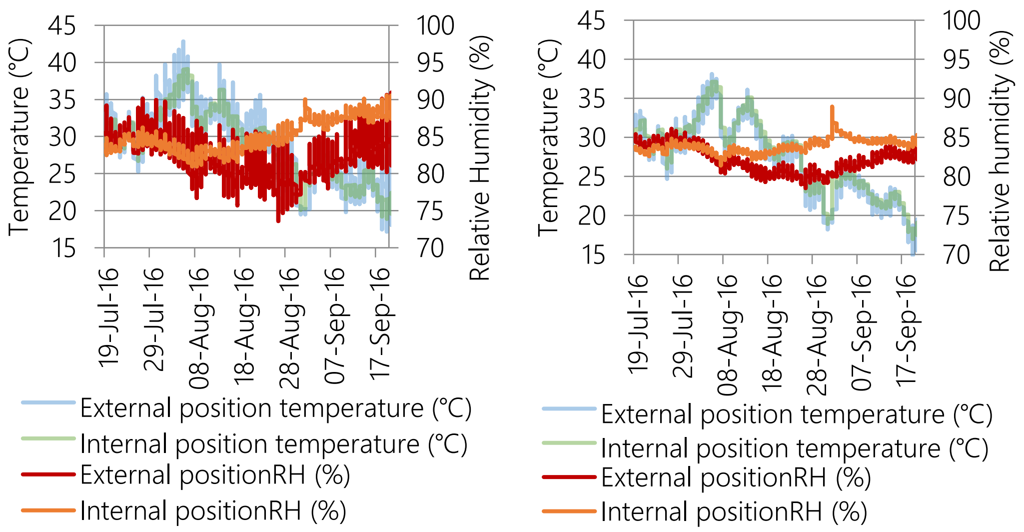


Figure 6.8. Initial RH decrease in the No.7 location (left) and the No.18 location (right)

The RH levels at all monitoring locations began to drop at the beginning of spring. The lowest recorded RH level was 26% at the location No.7 in 4th May 2017 (Figure 6.9). The RH levels of the location No.7 increased and fluctuated between 50% RH - 60% RH in June 2017. At the end of the monitoring research, the highest final RH data was achieved from the inner sensor location of the monitoring location No.19 (Figure 6.7). The monitoring results of all monitoring locations are shown in Figure 6.10- Figure 6.23

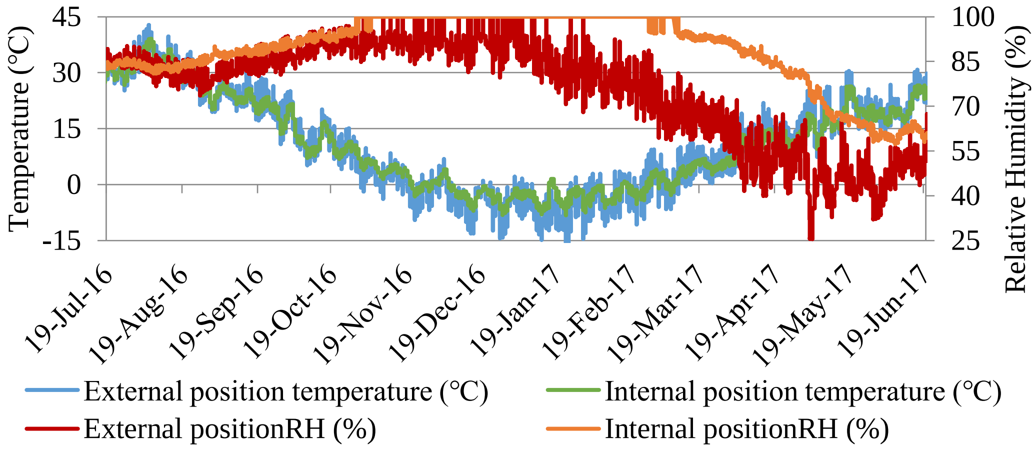


Figure 6.9. Monitoring data of relative humidity and temperature of the location No.7

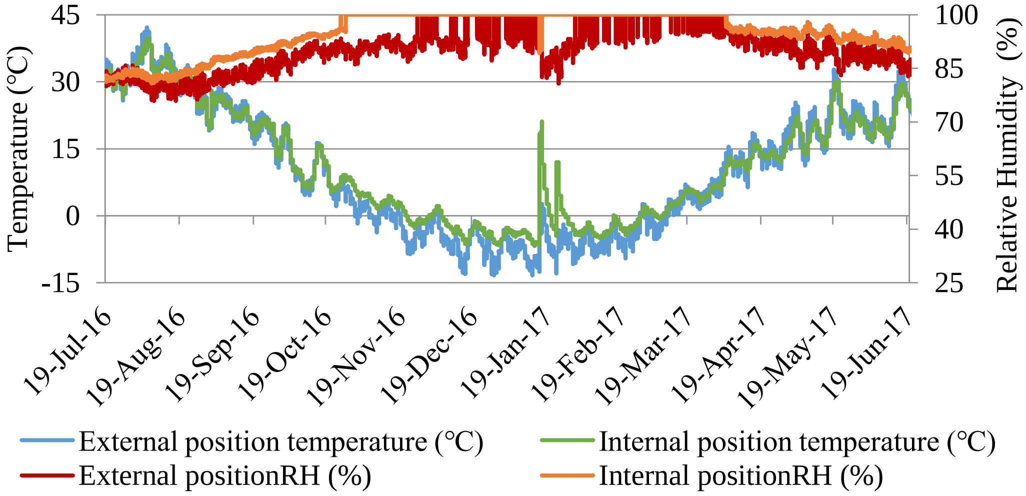


Figure 6.10. Monitoring data of RH/T of location No.1

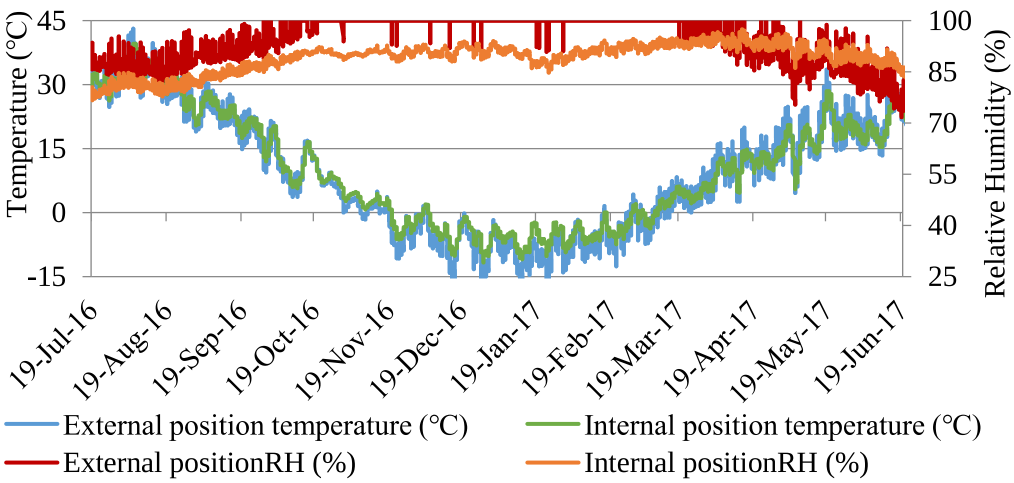


Figure 6.11. Monitoring data of RH/T of location No.4

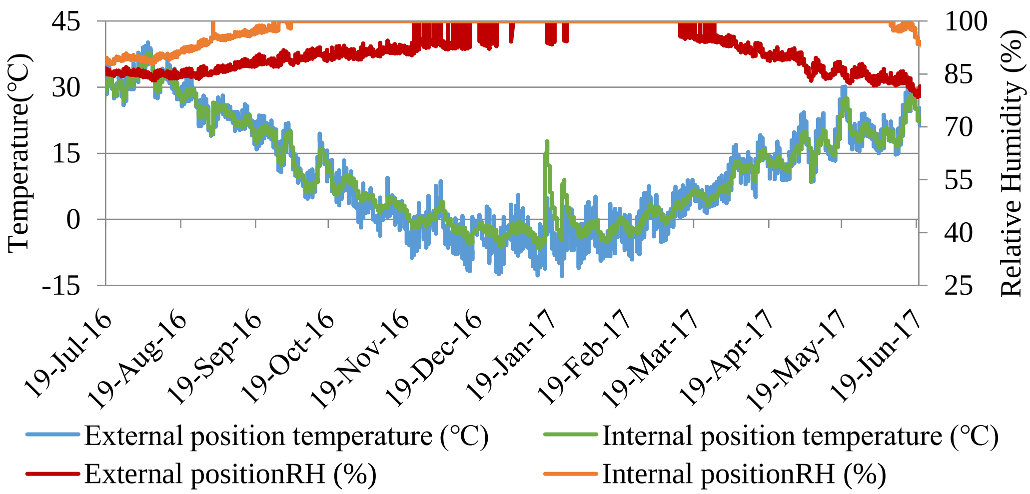


Figure 6.12. Monitoring data of RH/T of location No.6

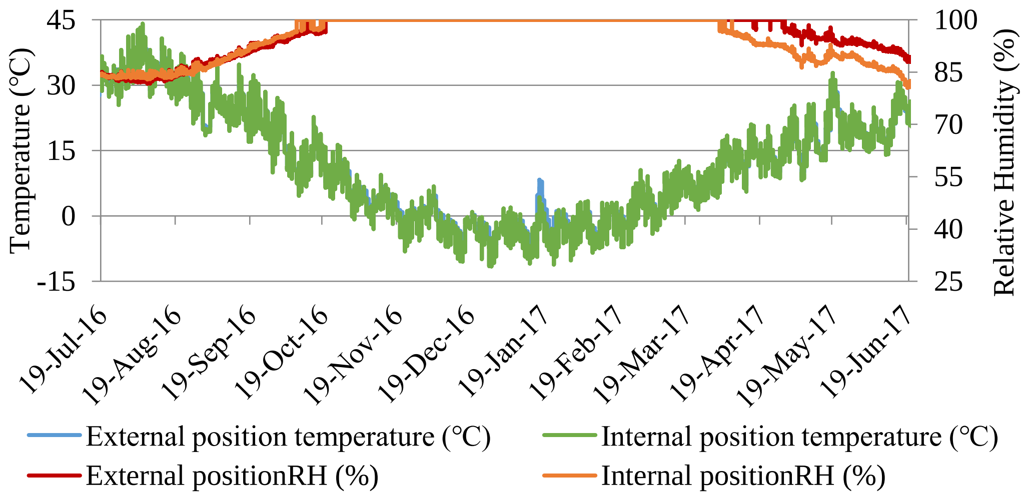


Figure 6.13. Monitoring data of RH/T of location No.8

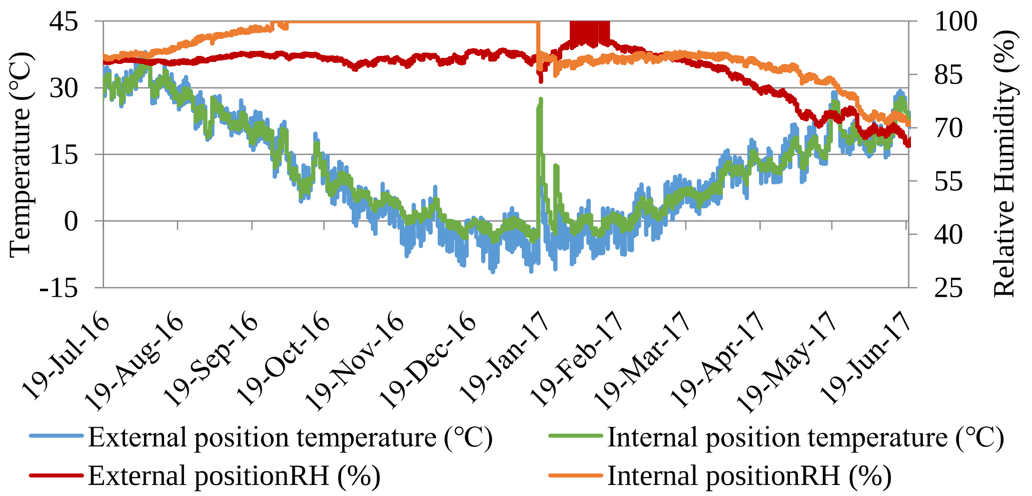


Figure 6.14. Monitoring data of RH/T of location No.9

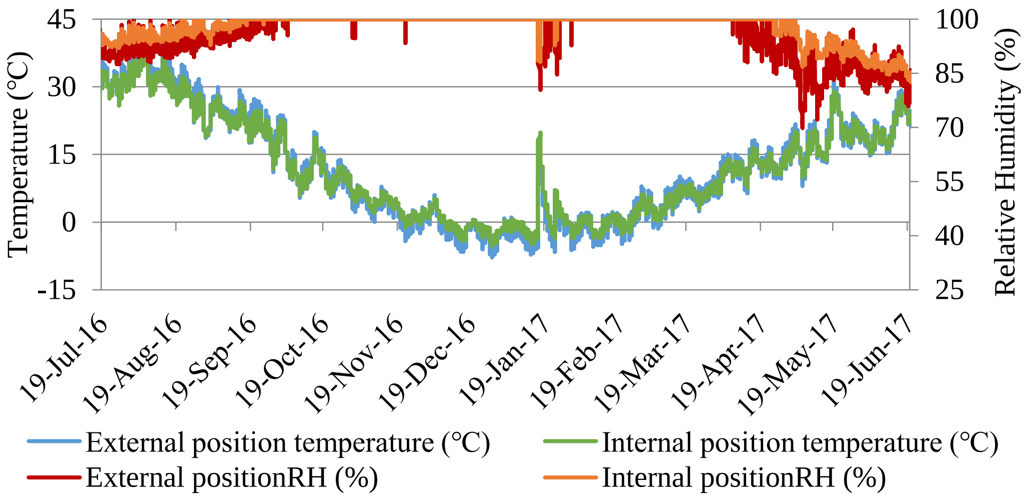


Figure 6.15. Monitoring data of RH/T of location No.10

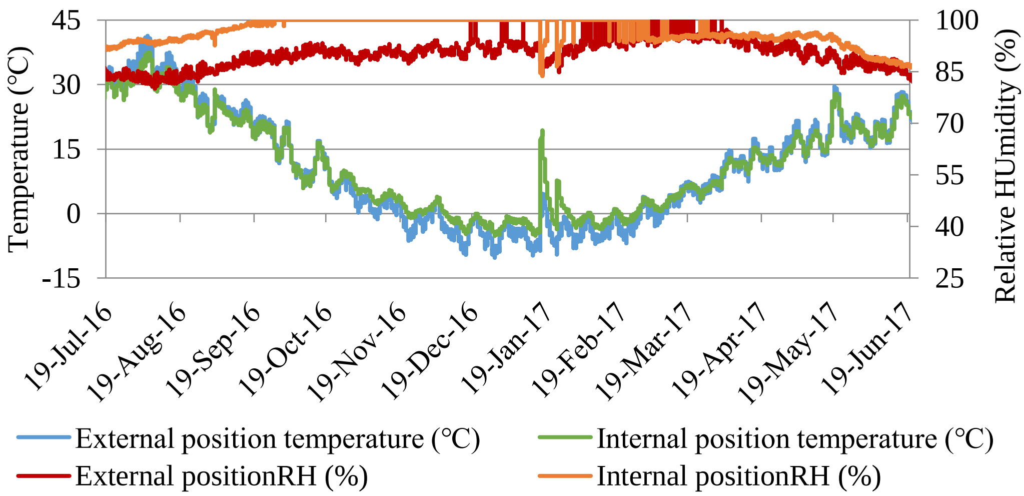


Figure 6.16. Monitoring data of RH/T of location No.11

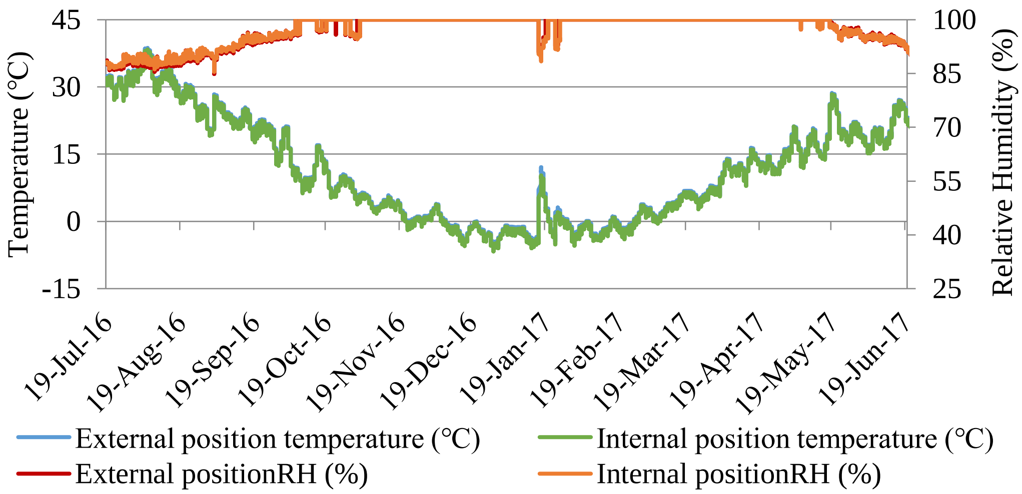


Figure 6.17. Monitoring data of RH/T of location No.12

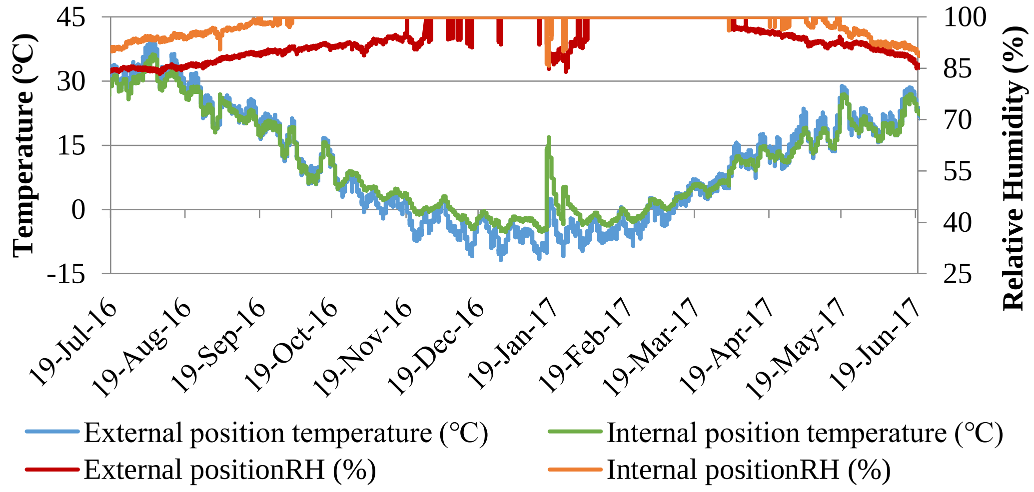


Figure 6.18. Monitoring data of RH/T of No. 13

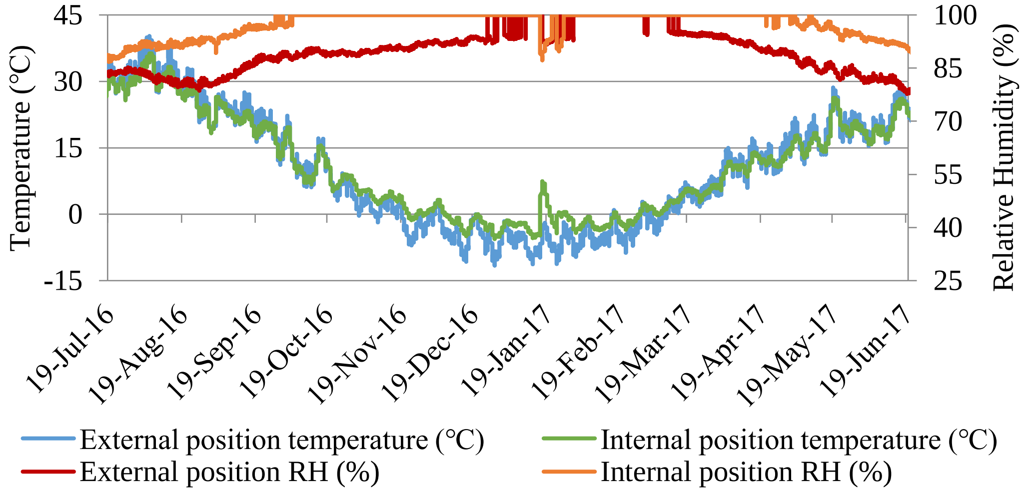


Figure 6.19. Monitoring data of RH/T of location No.14

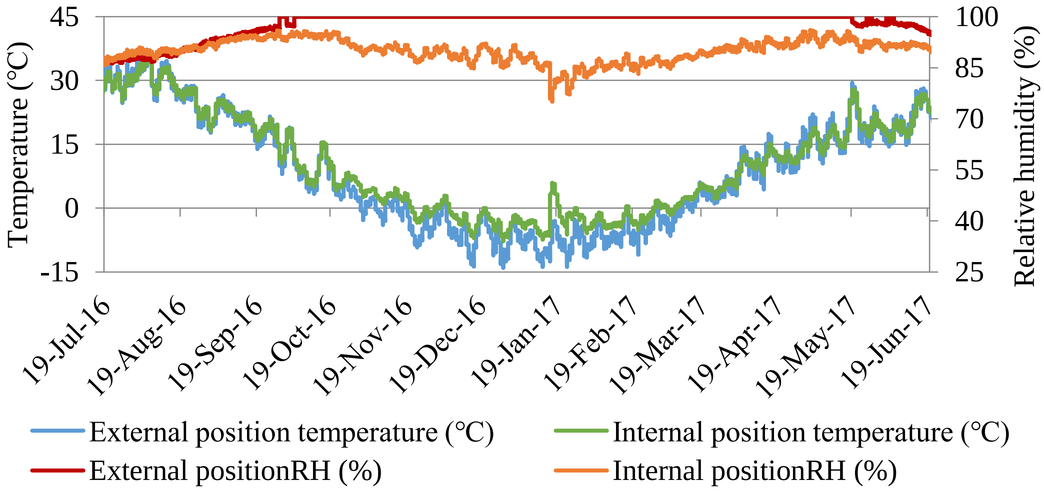


Figure 6.20. Monitoring data of RH/T of location No.15.

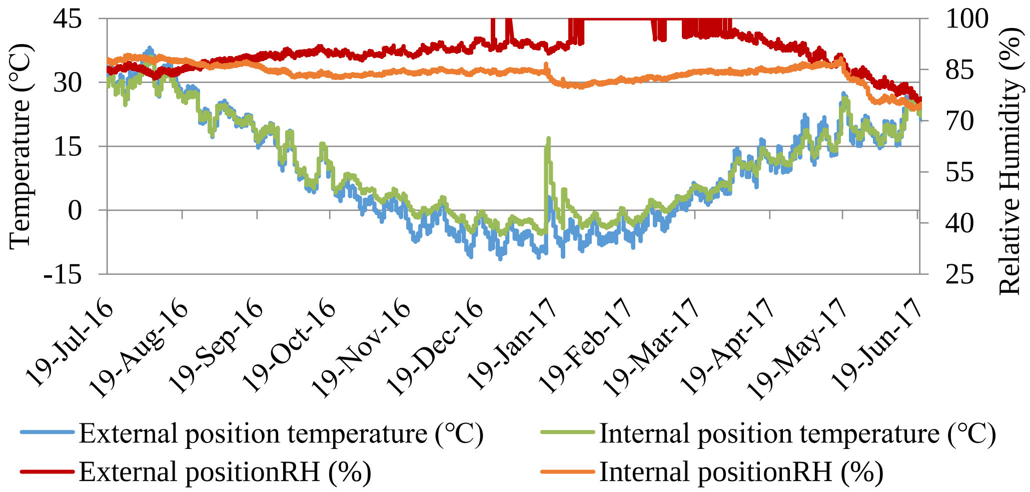


Figure 6.21. Monitoring data of RH/T of location No.16

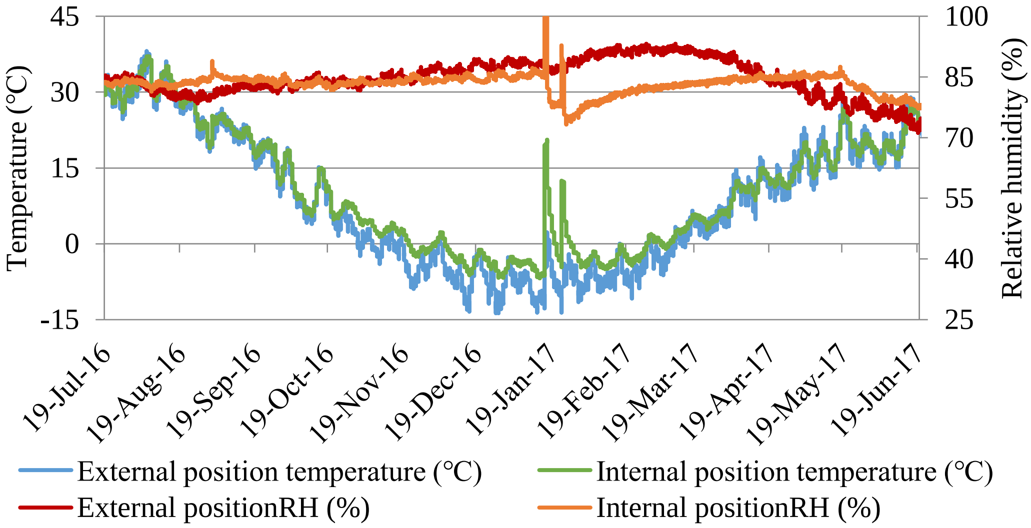


Figure 6.22. Monitoring data of RH/T of location No.18.

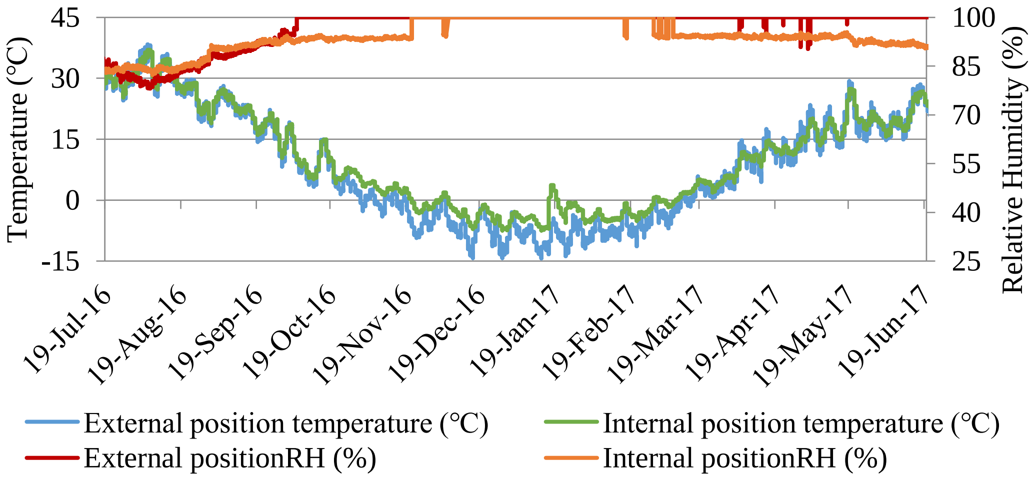


Figure 6.23. Monitoring data of RH/T of location No.20

6.2.2. Conversion of RH/T data

The monitored RH/T data can be used to indicate the hygrothermal environment within straw bale walls. However, it is difficult to predict either actual water content inside straw bale walls or vapour movement between straw bale walls and external environment. To estimate the actual vapour inside straw bale walls, the RH/T data can be converted to actual vapour data by making use the of saturation vapour pressure formula. The actual vapour pressure can be used to describe the drying process of straw bale walls and the effects of straw stacking on the process:

$$\text{Relative Humidity} = \frac{e_{actual}}{e} \quad (6.1)$$

Where:

$e = \text{Saturation vapour pressure in T}$

$e_{actual} = \text{Actual vapour pressure in T}$

The saturated vapour pressure can both be taken from the water vapour pressure table (Haynes, 2014) and calculated from existing equations (Alduchov and Eskridge, 1996). For the calculating equations, the temperature have notable impact on the accuracy of the results (Alduchov and Eskridge, 1996). Due to different properties of crystalline water and liquid water, there are few equations that can maintain high accuracy below the freezing point and above the freezing point (Alduchov and Eskridge, 1996).

The equation proposed by Tabata (1973) can produce accurate results within temperature ranges in the daily situations. The liner equation has maximum error range of 2% at -15ºC and less than 1% error range in -10ºC to 45ºC (Tabata, 1973) which is broadly similar to the monitored temperature range. By using the Tabata (1973) equation, the monitored RH/T data can be converted to water vapour pressure data to help to understand drying process of rendered straw bale walls:

$$\log_{10} e = 9.28603523 - 2.32237885\left(\frac{10^3}{T+273.15}\right) \quad (6.2)$$

Where:

$e = \text{Saturation vapour pressure in T}$

$T = \text{Temperature in degrees celsius}$

The vapour pressure of all monitored positions kept increasing to their highest level three weeks after the beginning of the monitoring period. The highest vapour pressure levels were around 76-77 millibars and they appeared in external sensor position of location No.10 (Figure 6.24). Other than the low positions on south facing walls, the peak vapour pressures of the monitoring positions were all below 70 millibars. Due to the driving wind from south of the experimental building introduce more water vapour in the south face wall during the rainy season at the beginning of the monitoring period, the lowest vapour pressure was monitored in the location No.18 (Figure 6.25). At the end of the monitoring period, sensor locations within south wall gave lower vapour pressure data than the ones within other faces of the walls. The vapour pressure levels at the monitoring positions continued to decrease in the following months and rose again after January 2017.

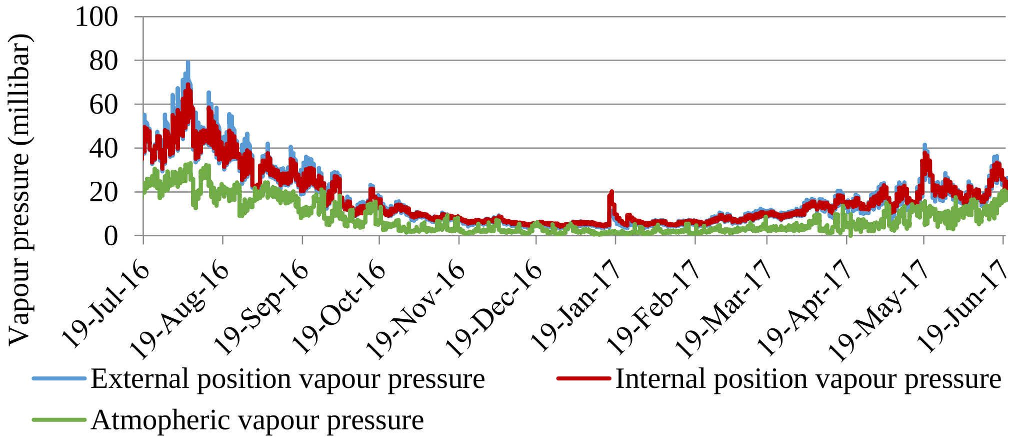


Figure 6.24. Vapour pressure of location No.10.

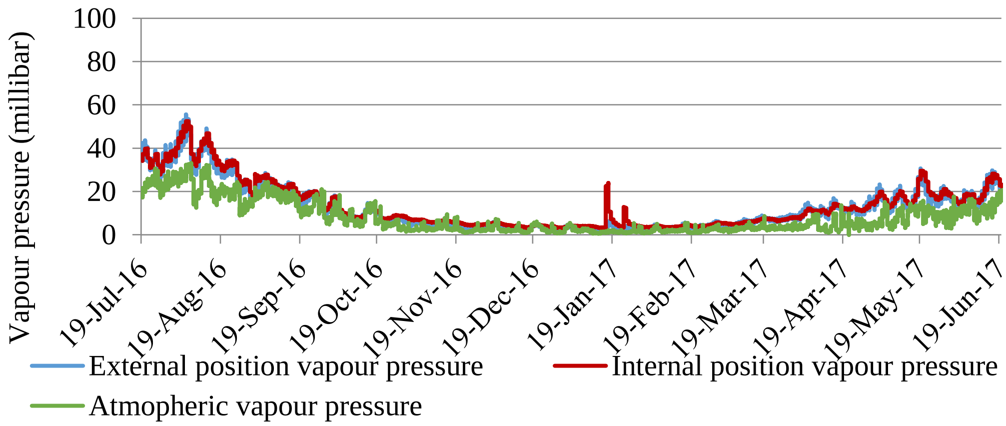


Figure 6.25. Vapour pressure of location No.18

6.2.3. Drying trend of straw bale walls

The vapour pressure differences between the sensor positions and the atmosphere can be used to describe the moisture movement between the straw bale walls and the atmosphere. Higher vapour pressure data at the monitoring positions than the atmosphere indicate that the straw bale walls are releasing moisture into the atmosphere at the data collecting point and vice versa. Fluctuations of the vapour pressure difference indicate that the straw bale walls have established an equilibrium moisture exchange between internal bales and the external atmosphere. As a result, fluctuations of the vapour pressure difference around 0 millibar is considered to be a sign of fully dried straw bale walls. The times at which the monitored vapour pressure data were higher than the atmosphic vapour pressure are highlighted in the blue rectangle in figures 6.24-6.26 and periods where vapour pressure fluctuated around 0 millibar are highlighted in Green in the same figures. Considering the unreliable monitoring data during winter months in the monitoring period, the vapour pressure data were analysed in two periods of time: The first period begins at the beginning of the monitoring research and ends at 1:00 am 19th November 2016; the second period was from 1:00am 19th February to the end of the monitoring research. Detailed drying trends of all monitoring locations are shown in Appendix B. There were in general three drying trends within the straw bale walls in the experimental building (Figure 6.26- Figure 6.28):

Firstly, the vapour pressure data show continuously higher vapour pressure data of the monitoring locations than external atmosphere within the north facing walls and east gable end wall (Figure 6.26). Because the vapour pressure data of the monitoring positions were higher than the atmospheric vapour pressure for the entire monitoring period, the drying process of the faces of straw bale walls was not complete during the monitoring period. The long drying process matches the continuously high RH data of the monitored positions. During the whole monitoring period, vapour travels from straw bale walls to atmospheric environment in the north face wall and the east gable end walls.

Secondly, the straw bales established vapour exchanges between external atmosphere and the south facing walls after spring (Figure 6.26). The vapour pressure data suggest that the vapour pressure difference between straw bales and the atmosphere were smaller in the second analysed period than the ones in the first analysed period and the vapour pressure difference fluctuated around 0 millibars after May (Figure 6.27). The vapour pressure difference indicates that the moisture within straw bales was continuously being released into atmosphere before spring in the monitoring research and the drying periods of the two facing walls were around 9 months to 10 months.

Finally, straw bales also show a significantly shorter period time to establish the moisture exchange between the walls and the atmosphere in the monitoring research (Figure 6.28). Vapour exchange of the south facing wall with laid-flat bales were established at the beginning of the second analysed period of time. Comparing to the south facing wall with laid-on edge bales, the significantly shorter drying period may be caused by different bale stacking methods. The effect of stacking methods will be analysed in Chapter 7.

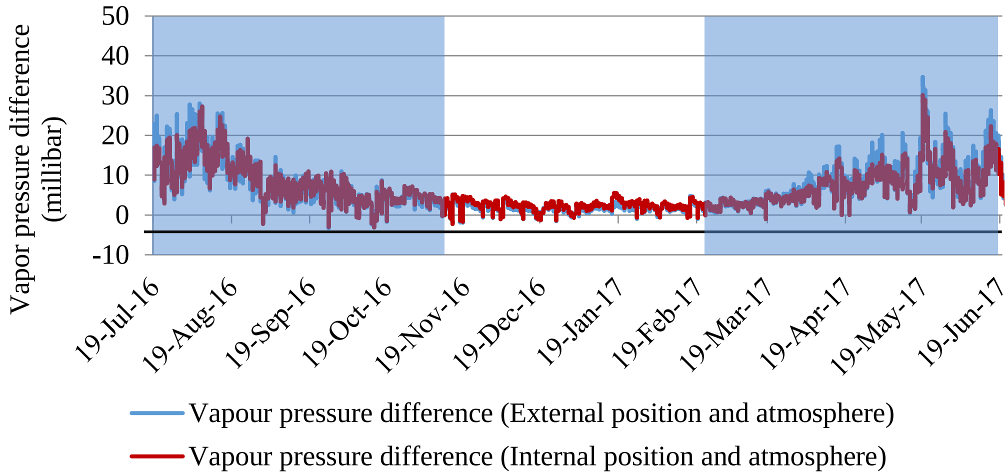


Figure 6.26. Vapour pressure difference of location No.15

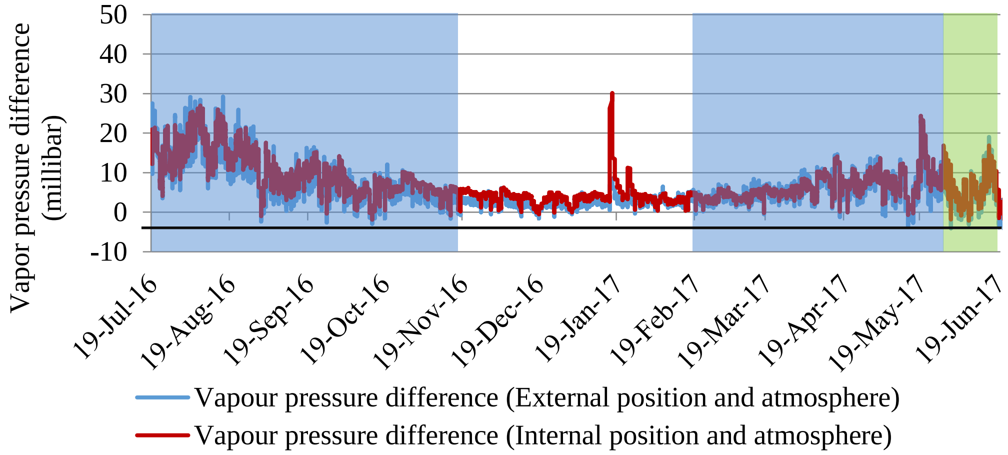


Figure 6.27. Vapour pressure difference of location No.8

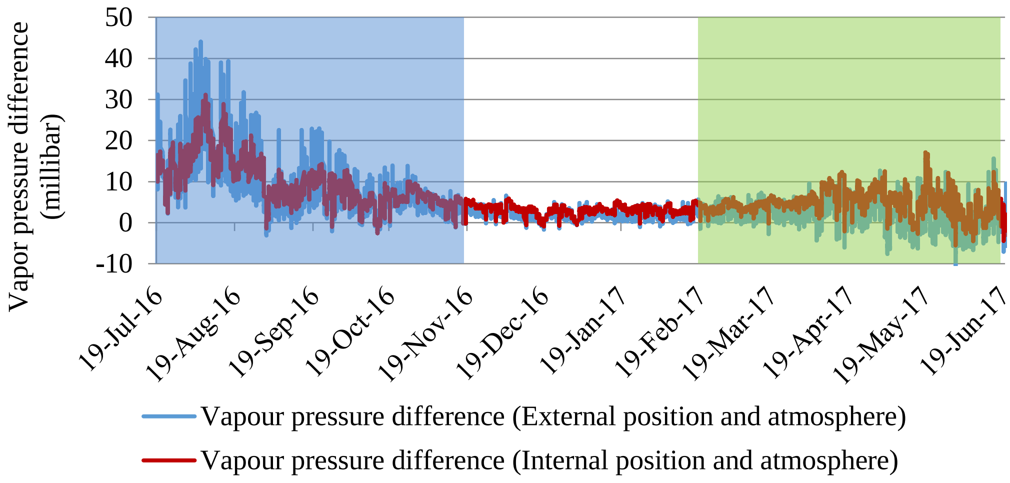


Figure 6.28. Vapour pressure difference of location 7.

The vapour pressure results suggest potential condensation within straw bale walls. During the heating process of the building, the monitoring RH/T changed significantly because of a much warmer internal space. The actual vapour pressure data of each monitored position were also increased significantly during the heating process. Since the straw bale walls were sealed by rending layers and plaster layers, the increasing vapour pressure within straw bale walls was mostly from moisture inside the lime stucco. As a result, the monitoring RH data suggest that the internal air was fully equilibrated with atmospheric conditions, it is highly possible that the vapour became condensation and ice when temperature dropped down to 0℃ at the end of October. The condensation would become ice when temperature drops below 0℃ and therefore the condensation would initiate degradation during winter time. However, the frozen ice will become liquid water when temperature rises again above the freezing point after March 2017.

6.3. On-site visits of the experimental buildings

6.3.1. Initial winter visit

During the first on-site visit (16th January 2017 to 18th January 2017) to the experimental straw bale building, the straw bale walls were found to be in good condition based on visual inspection and infrared images of the straw bale walls. Comparing with the condition after construction, there was no notable change to the walls. The lime render withstood low winter temperature and there was no noticeable cracking after the initial drying process of the outer layer of the lime render. A comparison of the lime render and the cement render in the ADRA project (Figure 5.11) demonstrates that the lime render would be a more suitable rendering material (Figure 6.29). The cracks of lime renders were generated initially due to drying process of the lime render. The cracks did not propagate onwards after the curing process of the lime render of the experimental building.

Figure 6.29. The lime render in this research.

The infrared image of the straw bale buildings also suggests that there was no significant thermal bridging through the straw bale walls (Figure 6.30). From the thermal image, the surface temperature of the end wall with infill straw bale has lower surface temperature than the EPS insulated columns. If the straw had undergone serious degradation before the onsite visit, the thermal image would present thermal bridging caused by hollows within the walls. The thermal bridging free straw bale wall suggests that the straw within the walls remained in good condition and there was no significant degradation within the walls. As a result, the straw within the walls can be considered to be well constructed and with no notable degradation of straw within walls.

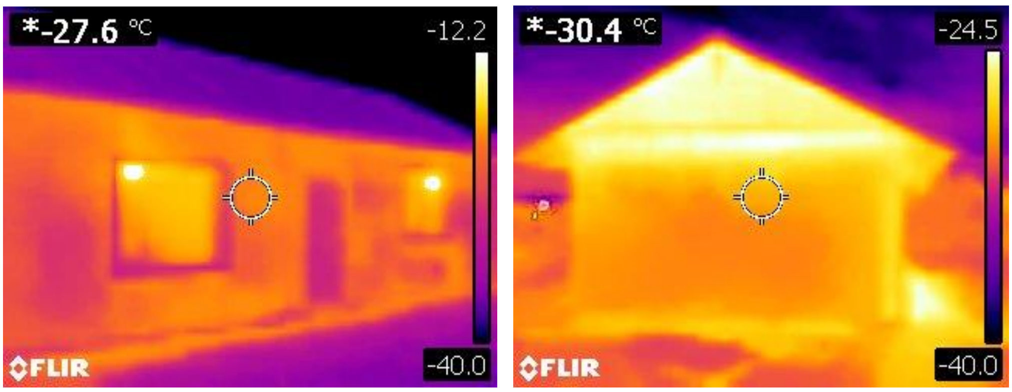


Figure 6.30. Thermal image of south wall (right) and west end wall (left).

The straw within walls was also examined through a 'truth' window on internal surface of the north facing wall with laid flat straw bales. The truth window was installed in the internal surface of the north facing wall with laid flat straw bales during the construction phase of the building. The truth window was located a central point on the internal surface wall. Despite high monitored RH and long drying process in the location No. 19, the straw can be seen to be in good condition (Figure 6.31). The colour of straw stays unchanged during the site visit and there was no notable sign of straw degradation of the straw behind the truth window. The straw condition behind truth window suggests that straw have not experienced serious degradation in the way that the monitoring data would imply.

Figure 6.31. Straw in Truth window after completion of the experimental building (left) and during the first onsite visit (right).

6.3.2. On-site visit at the end of monitoring research

To examine the straw conditions behind rendering layer, rendering layer of 8 monitoring positions (Table 6.2) were removed to expose the straw inside the bale walls in the second onsite visit after 11 months monitoring research on 19th June 2017. The straw was visually checked onsite.

There was limited degradation of straw at the interface between straw bales and external rendering for all opened positions (Figure 6.32). The degradation appears on the interface of lime render and straw bales and penetrated 2-3 cm deep into the straw bales. The straw behind the interface remains golden colour inside the walls. The site visit confirms that the straw was in good condition inside the straw bale walls for the entire monitoring period. Unlike the limited straw degradation on the interface between straw bales and the lime render layers, the straw was in good condition with mixture of lime render (Figure 6.33).

Table 6.2 Rending thickness of opening locations and measured moisture.

Monitoring location	Actual moisture content		Actual RH from sensors	Render thickness
No.1	Inner	20.3 %	85.1 %	75 mm
	Outer	28.0 %	90.5 %	
No.4	Inner	15.3 %	74.9 %	65 mm
	Outer	24.0 %	85.7 %	
No.9	Inner	12.8 %	65.5 %	50 mm
	Outer	14.6 %	71.7 %	
No.10	Inner	17.3 %	81.0 %	70 mm
	Outer	21.0 %	83.7 %	
No.11	Inner	18.0 %	83.8 %	105 mm
	Outer	23.0 %	86.8 %	
No.12	Inner	28.6 %	91.9 %	40 mm
	Outer	33.0 %	92.1 %	
No.18	Inner	17.0 %	77.8 %	50 mm
	Outer	14.0 %	72.7 %	
No.19	Inner	24.0 %	86.0 %	100 mm
	Outer	16.0 %	82.6 %	

Figure 6.32. Opening of external render (left) and straw adjacent rendering layer (right) of location No.19

Figure 6.33. Mixture of straw and lime stucco outside location No. 18.

More serious degradation was identified in the north facing wall than the other facing walls. The degradation trends map the analysis of degradation potential of monitoring data. The monitoring research has identified longer drying process than the other facing walls. The experimental research on high RH/T environment has shown resistance of degradation of straw in the initial high RH/T situation in the monitoring research. The degradation may be associated with the long drying process of the straw bale walls and the resultant condensation at the interface between straw bales and rendering.

The thickness of lime rendering varies significantly from the design thickness (Figure 6.34). The thickness variations of lime rendering was between 40mm to 105mm in the experimental building (Table 6.1). The thicker lime rendering layers may provide more moisture buffering to straw bales and introduce more initial moisture in the straw bales at the drying stage of lime rendering. The bales behind the thicker lime rendering would have higher initial moisture content and have longer drying period than the one behind thinner lime rendering. However, the thicker lime render layers do not have significant effect on straw degradation from visually inspection.

Figure 6.34. Straw conditions behind opening locations with thin rendering thickness (left) and thick rendering thickness (right).

6.4. Summary

The outcomes of the construction process show how significant an impact the skills of builders and local weather can have on the construction of a straw bale building. As the workers onsite had limited understanding of straw bale buildings many delays were involved in their work including wrong installation of the base plate and incorrect application of the lime render. The local weather also had a notable impact on the construction schedule. Around 3-4 weeks delay to the construction schedule was attributed to the early arrival of the rainy season. The unexpected rainy days also resulted in damage to 30% of the total straw bales during onsite storage.

The subsequent monitoring research recorded 11 months data of the hygrothermal environment within the experimental building from 19th July 2016 to 19th June 2017. The monitored temperature increased to their highest levels in the first month. Monitored temperatures continued to drop over the following months and reached their lowest point in January 2017. Temperatures at the monitored locations increased again with the coming of spring in the subsequent months. The monitored RH also showed a notable increase in the first 2 weeks of the monitoring research. The RH levels decreased marginally over the next 2 weeks and then increased to their highest level in the following 3 months. The majority of the monitored RH levels reached 100% RH during winter months and decreased in the following spring months.

Even though the monitored results showed 100% RH at monitoring positions over winter months, the high RH level is likely be overestimated. The monitored 100% RH would either be a result of non-functional sensors or the results of condensation of ice over the sensors. The 100% RH situation appeared in most of the monitoring locations. The duration of this situation was from the end of September 2016 to the beginning of May 2017. The duration showed minor differences at different monitoring locations.

The RH distribution through the walling section showed two major trends depending on the walling orientation. The monitored RH levels of external sensor locations were higher than the inner ones in the south facing walls, east gable end wall and the west gable end wall whereas the inner position sensor monitored constantly higher RH levels than the outer positions in the north facing walls during the monitoring period.

The drying processes of the straw bale walls can be evaluated by converting the RH/T data acquired from the monitoring research to vapour pressure data. Vapour exchanges between straw bales and external environment were only observed inside the south facing walls. For the other walling faces, vapour pressures inside straw bale walls were constantly higher than the external environment for the other walling faces. As a result, the drying process of the south facing straw bale wall is considered to have completed by the end of the monitoring period whereas the process was still ongoing in other wall elevations. Comparison between the completed drying processes of the laid-flat bale wall and laid on-edge bale wall showed that the flat stacking bales undergo a faster drying process. The straw bale wall with laid flat bales achieved a fully dried state at the beginning of spring which was 2 months earlier than for the laid on-edge bale walls. The effects of different stacking method will be analysed in the next chapter.

There were two separate onsite investigations of the experimental building both during the monitoring research and at the end of the monitoring period. No significant straw degradation was identified during either of the site visits. The presence of thermal bridging within the walling construction was checked using an infrared camera in the first site visit, which verified that no thermal bridges existed. The physical condition of the straw was checked to be found in good condition through a truth window in the north facing wall. More intrusive inspection methods were applied during the second site visit involving drilling and opening up of the lime render. Straw was found to have marginal degradation behind lime render. The degradation appeared directly behind the lime render and penetrated into the straw bales to a depth of 2-3cm. The opening up of lime render also identified inconsistent thickness of lime render in different places. The thicknesses of lime render ranged from 40mm-105mm in different drilling positions which were notably thicker than the original designs. Despite the different thickness of lime render, no notable differences of straw degradation were identified with respect to render thickness. However, the thicker lime render than the original designs introduced more initial moisture to straw bale walls and extended the drying process of the straw bale walls.

7. Analysis and Discussions of the research findings

This chapter analyses the results of the three stages of research. Based on the laboratory experimental results from Chapter 4, of susceptibility of straw degradation, the suitability of predicting models of straw degradation is firstly discussed and analysed. The second part discusses the issues identified from Chapter 5 during the building investigation process of the existing straw bale buildings in northern China. Thirdly, the susceptibility to degradation of the straw bales in the experimental building, from Chapter 6 is analysed by applying the modified predicting models for straw bales. This chapter finally proposes suggestions on further straw bale building which takes into account of the research findings in previous sections.

7.1. Modification of existing Isotherm model

Reviewing the experimental results of adsorption isotherms in the DVS method, the sorption isotherms of rice straw and wheat in this research do not closely correlate with the equation (2.2) of Lawrence et al (2009b) which has been presented in the section of 2.4.2. At all RH levels in the DVS method, moisture contents of rice straw and wheat straw show 1%-2% less moisture content than that given by the equation of Lawrence et al (2009b). Lawrence et al (2009b) based their equation on full equilibrium at each RH set point, but the data in the present study are based on accepting an equilibrium when dm/dt < 0.002g/min up to 70% and on a set time above that RH level. This introduces a systematic error. Since the primary value of sorption isotherms is to model performance, it is proposed that the use of a more rapid kinetic, such as the one used in this study, is more realistic than to use data achieved from complete equilibrium. A modification to the Lawrence equation to account for this change in the kinetic can be achieved by simply changing the constant 'n' in equation (2.2) from 44 to 54 based on the empirical results from the sorption isotherm of the DVS method:

$$C = \frac{C_s}{1+n(\frac{K_m}{\varphi}-1)^{i/3}} \quad (2.2)$$

Where:

$C = moisture\ content\ at\ relative\ humidity\ \varphi$

$C_s = fibre\ saturation\ moisture\ content\ (400\%)$

$\varphi = relative\ humidity$

$n = 44$

$K_m = 1 - K_c = 0.9773$

$i = 1.6$

The Lawrence equation fitted the moisture content of specimens of desorption cycles of the DVS method. The modified equation would be used to predict the moisture content of wheat straw and rice straw in the sorption cycle and the Lawrence equation can be used to predict the moisture content of wheat straw and rice straw in the desorption cycles. Applying modified equation results in a modelled isotherm which is much closer to the data produced by this study. Limiting the period of adsorption to 1600 mins prevents the straw from reaching an equilibrium with the environment (as typically demonstrated by a dm/dt of <0.002mg/min) and therefore approximates more realistic conditions, as such high periods of relative humidity are typically maintained for more than 1600 minutes (Figure 7.1). Dynamic hygrothermal measurements, such as moisture buffering (Latif *et al.*, 2015), will begin to provide representative real moisture sorption, but is outside the scope of this research.

The results of the DVS method show that the open ended straw reach equilibrium quicker than the open end straw in all RH levels. The effect of open ended straw will likely depend on the relative ratio of exposed ends to the predominant surface area of the stem wall, and therefore the aspect ratio of the straw. The aspect ratio of the specimens in this investigation are not of typical in straw bale constructions and therefore the findings still need to be validated through further research on moisture movement of full scale straw bale walls. However, this finding may contribute to selection of the stacking method of straw bales in different climatic conditions, and modifying the makeup of a straw bale specifically for construction purposes.

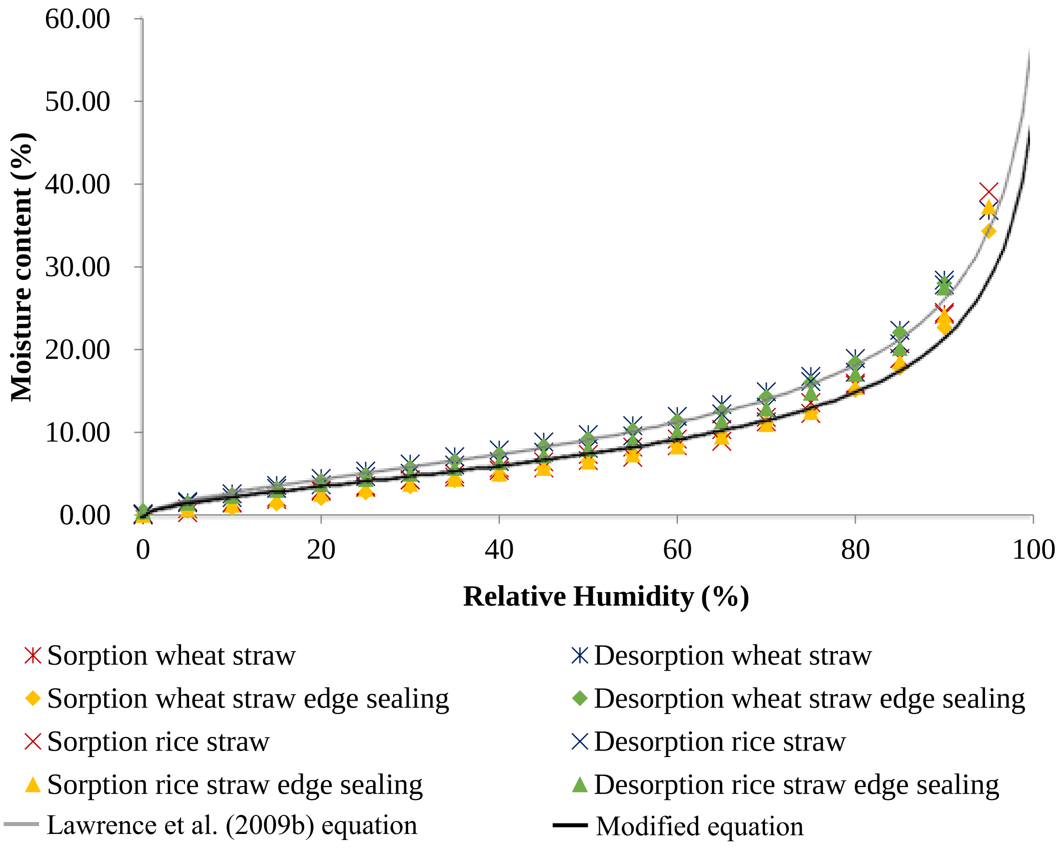


Figure 7.1. Proposed equation with results of DVS method and equation of Lawrence et al. (Lawrence *et al.*, 2009b).

7.2. Analysis of outcomes of building investigation of existing straw bale buildings

The building investigation of the existing straw bale buildings have shown different construction detailing of straw bale walls comparing with the one worldwide. The following section firstly discuss and analyses the effectiveness of the building strategies which takes into account the straw bale constructions worldwide. The outcomes of the interviews of local residents are discussed in the following section. As cracking issues are widely shown in the ADRA project in Jiamusi, the issue is detailed analysed through computational simulation of the walling constructions in context with local climatic conditions.

7.2.1. Comparison of existing Chinese constructions and global constructions

Chapter 5 presnets notable differences between the existing straw bale buildings in northern China and the straw bale constructions worldwide. The project in Jiamusi is the largest single development of straw bale building in the northern China. Taking account of construction quality and the condition of the straw bales, the houses in Jiamusi are still in relatively good condition. The combination of brick and concrete structure with straw bale infill walls have been shown to be a superficially effective building form for farm houses in rural northeast China. There are general four notable differences have been identified:

a. Insufficient insulation material and thermal bridging problems.
b. Connection with the foundation
c. Fixing method of straw bale walls
d. Type of render.

a. Insufficient insulation material and thermal bridging

According to the training manual and the standard, the primary structure of the straw bale buildings are not fully insulated to withstand cold temperature from November to March. The designs of the straw bale houses in the ADRA project do not involve thermal insulation layer for the brick columns and the thickness of the thermal insulation layer is not thick enough around the concrete beams (Figure 5.6). Therefore the thermal insulation designs may not be suitable for buildings in Jiamusi as the temperature of Jiamusi can reach lower than -20℃ in winter (Figure 7.2).

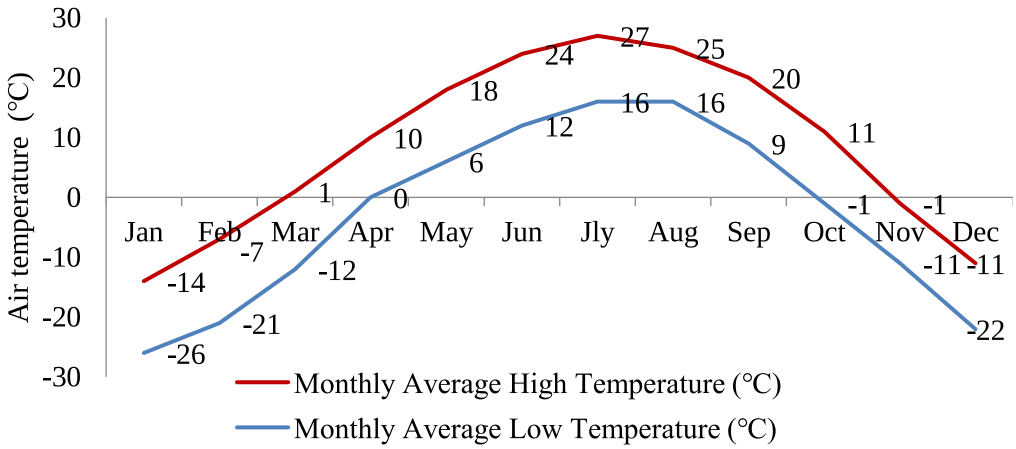


Figure 7.2. Monthly temperature in Jiamusi. (Weatherbase, 2017)

The effect of the thermal bridging was observed within the houses in Jiamusi. High thermal conductivity of the primary structure elements resulted in internal surface temperature lower than the freezing point and therefore frost was identified in the buildings in Jiamusi through site visit (Figure 5.9).

The thermal bridging issues would also lead to cracking issues of the rendering construction in the straw bale buildings. Considering the low air temperature in Jiamusi, the insufficient thermal insulation material will cause significant temperature difference between the surface of rendering construction covering structural elements and the one covering the straw bales (Figure 7.3). The temperature difference will lead to differential thermal expansion of the rendering construction covering the adjacent area of straw bales and the structural elements. Rendering construction are identified to have cracks around the adjacent areas of bricks and straw bales (figure 5.11 & Figure 5.12). As cracks are generated on surface of the rendering layer, liquid water and moisture has direct pathway to the straw bales and can lead to serious degradation of straw within walls (King, 2006). Detail discussion of the thermal bridging issue is included in the following section.

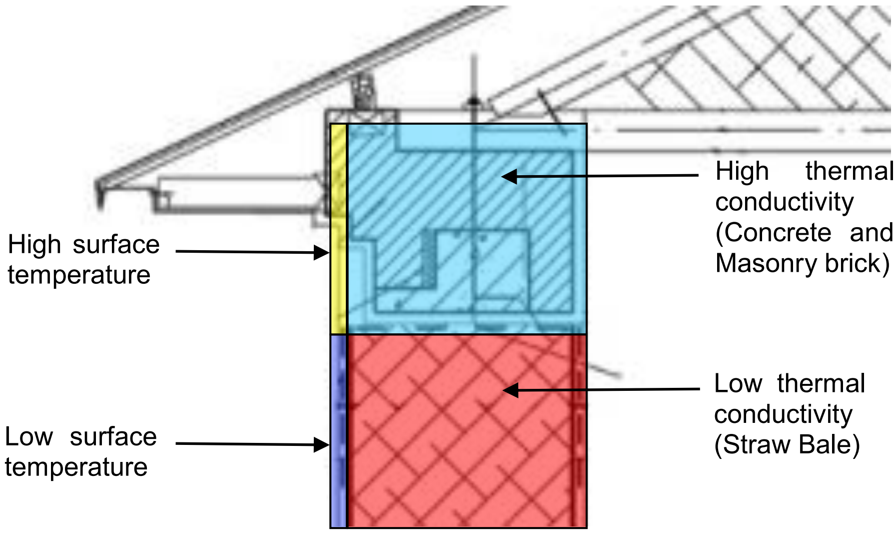


Figure 7.3. Cracks on surface rendering construction caused by different thermal expansion of rendering in different area.

b. Connection with the Foundation

The toe-up designs discussed in Chapter 2 is different in on the ADRA project and is not discussed with respect to the steel frame farmhouse. A unique connection with the foundation was developed in the ADRA project and referred to as the knee wall toe-up. The knee wall toe-up is designed to sit on a concrete ground beam which casted onsite (Figure 7.4). Due to the floor construction of the internal space is higher than the ground beam, the knee wall toe-up is directly against the ground level below the internal space which forms a direct pathway for underground moisture to travel into straw bales. Damp issues are long term processes, and any water damage may not be initially evident in leading to degradation of straw bales (Myhrman, 1998; Jones, 2009). However, the direct connection of straw bales and raising damp will lead to elevation of moisture content of straw bale in a long run and therefore bale conditions within the walls are likely to be a concern after long term exposure to underground moisture.

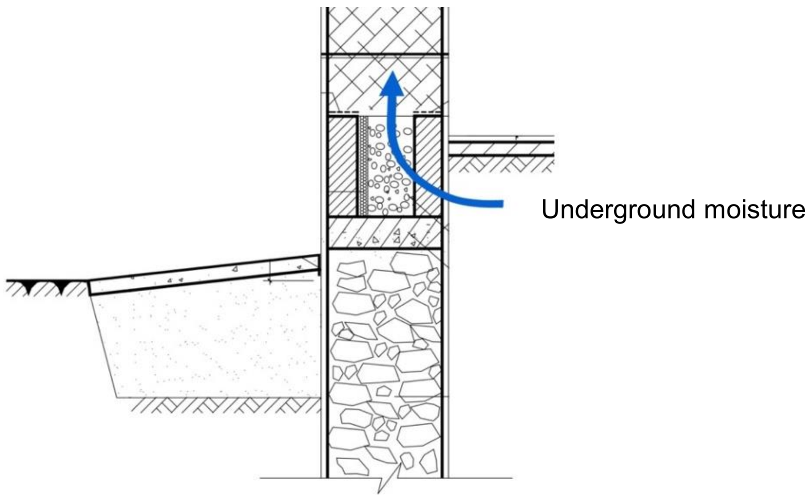


Figure 7.4. Potential ground damp damage routine (blue arrow) of foundation design of ADRA project.

c. Fixing method of straw bale walls

The metal mesh connection of straw bale walls is uniquely developed for existing straw bale practices in China. Compared to the widely used pinning system, mesh connections in the ADRA project would be weaker in preventing movement between bales during construction stage. In the pinning system, the pins are embedded in each layer of straw bales during the stacking process of the bales and therefore each layer of bales have been fixed before stacking of upper layer of bales (Jones, 2009). Due to the application method of the metal mesh, fixing can only be applied after completion of whole stacking process of straw bales. In the ADRA project and the steel frame farmhouse, straw bales are only fixed by friction between different bales during stacking stage of straw bale walls and therefore mesh fixing would be weaker in preventing movement between bales than the pinning system during the stacking process of bales. As the instability stacked straw bale walls will increase difficulties of buildability of straw bale walls, potential problems relating qualities of straw bale wall may be a concern of the straw bale walls in the current practices in northern China.

The quality issues of the metal mesh fixing method may be more significant in consideration of creating weaker boundary between straw bales and rendering constructions. In comparing the pinning system for fixing straw bales, as rendering materials do not have sufficient penetration to the straw bales with the metal mesh layer, a weaker boundary is formed (Jones, 2009). As solid connection between straw bales and rendering construction is crucial for increasing stability and shear force resistance of straw bale walls (King, 2006; Aschheim *et al.*, 2014), the straw bale walls would be problematic in resisting seismic force.

d. Render types

The render in China consists of a number of different layers. The idea of using different layers is to form a flexible intermediate layer between the straw and other renders and therefore increase stability of the rendering construction (Cao *et al.*, 2010; (DCHP), 2007). Only the ADRA project ((DCHP), 2007) and the steel frame farm house project (Cao *et al.*, 2010), use these multiple render layers. However, the method is not mentioned in any other research or construction practices and the effectiveness of the rendering construction is highly doubtful. Renders elsewhere in the world generally use a single render material rather than combination of different materials.

Renders of straw bale walls should be breathable enough to provide downward trend of moisture content of straw bales within walls (Bergeron and Lacinski, 2000). Lime based rendering constructions and cement based rendering constructions are suitable for straw bale buildings in northeast China in consideration of render strength. (Yang *et al.*, 2010). However, due to significantly better breathability than cement render (Jones, 2009), lime based rendering construction is a better rendering construction than existing one in the ADRA project and the steel frame straw bale farmhouse.

7.2.2. Analysis of cracking issues in the ADRA project in Jiamusi

As demonstrated in previous section, straw bale buildings have significant potential for thermal bridging through the concrete and masonry structure. The current status of straw bale buildings in Jiamusi may therefore have potential issues relating both to thermal bridging and to straw degradation due to cracking on external surface of rendering construction. To justify the effect of insufficient insulated structural elements in the ADRA project, both visual inspection and computational simulation were conducted.

To verify the thermal bridging issues, the ADRA design is modelled using THERM 7.4.4. The modelled areas are the joint constructions of gable ends and straw bales, of south and north walls and a section through the gable ends (Figure 7.5). There are three sections of walls in the simulation process. The joint constructions can be deduced from the drawing of construction detailing of the wall section (Figure 5.6). The wall section is referenced from the layout of the design of farmhouses in the published standard by DCHP (Figure 7.6).

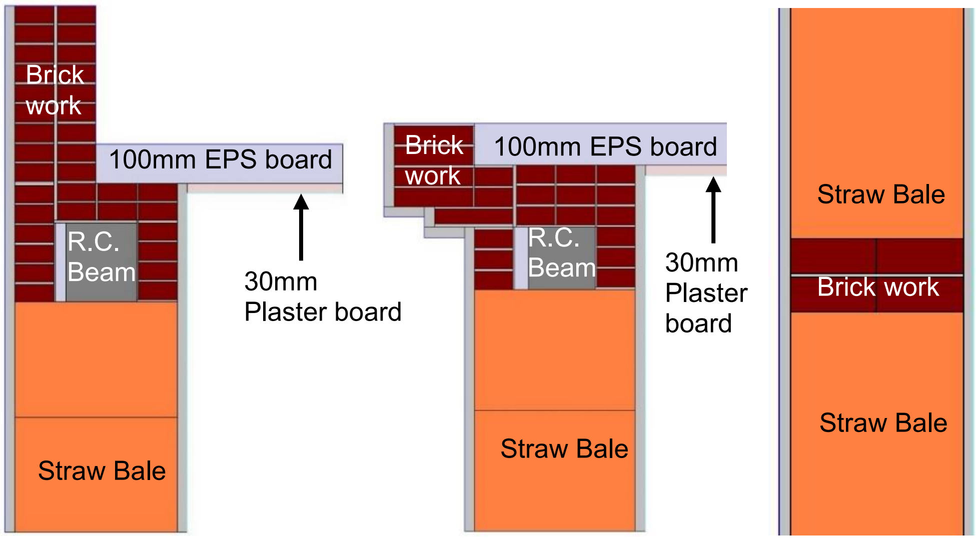


Figure 7.5. The joint construction of sidewall (left), Joint construction of south and north wall (middle) and section of sidewall in the THERM simulation.

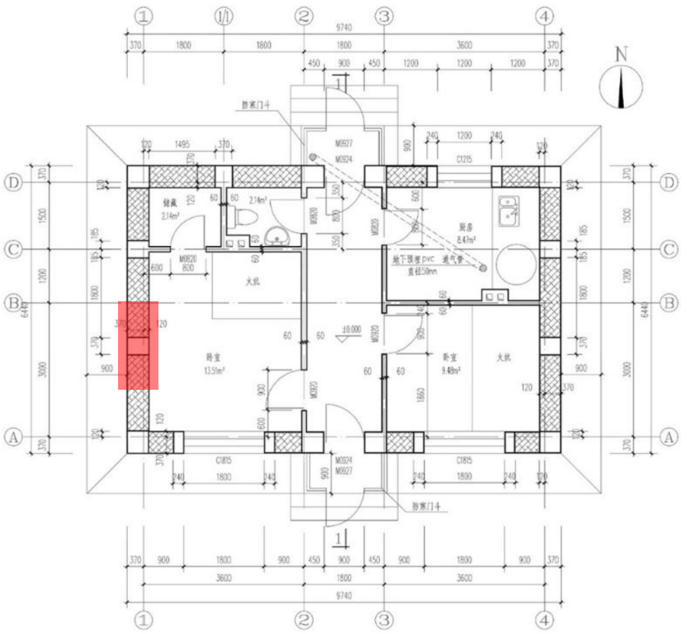


Figure 7.6. Layout of design of farmhouse in the ADRA project in Jiamusi and simulated section of gable end (in red). (Redrawn from ((DCHP), 2007))

The thermal simulation uses an external surface (external surface of rendering construction) temperature of -30℃ which is representative of winter air temperatures in Jiamusi. The internal temperature is set at 16℃ which is typical of indoor air temperatures in farmhouses in the rural areas of northern China (Zhang, 2006). Thermal conductivity of each building material in the simulation process is listed in Table 7.1. The use of mortar between straw bales is only referenced in the unpublished manual, and there is no evidence that existing straw bale buildings have applied such a construction method in northern China, and therefore has not be modelled.

Table 7.1. Thermal conductivity value used in THERM simulation.

Building Material	Thermal conductivity (W/mK)	Reference
Straw bale	0.07	(Shea *et al.*, 2012)
EPS board	0.038	From THERM database
Ceiling board	0.061	
Cement mortar	0.93	(Li and Fu, 2005)
Reinforced concrete	1.28	
Masonry brick	0.81	

While the wall constructions in Figure 7.5 are idealised, the effect of actual construction may result in different performances and therefore could be considered. A gap between the EPS board and the brick frame is included in the simulation process to take account of poor quality installation. This simulated installation error consists of a 2mm vertical linear gap between EPS board and the brick work in the joint construction of gable end and joint construction of south and north wall. The gap is in the range of allowable error in the Chinese standard (GB50210-2001, 2001).

The simulation results (Figure 7.7), show serious thermal bridging issues in the ADRA project in Jiamusi, with the majority of the heat loss associated with the non-straw bale elements. There is a clear linear boundary at the straw bale and brick-concrete interface in the thermal transmittance simulation. Heat transfer through straw bales is approximately 0 W/m^2 whereas it is 26-36 W/m^2 for the brick work for the joint design and 26-53 W/m^2 for gable ends. The concrete beam conducts the most heat through internal space to outside, forming clear thermal bridging in the joint design of south and north wall. The heat transmittance figure shows that heat is mostly exchanged through non-straw bale elements. The heat transmittance figure show that the design of non-insulated structural elements is problematic and result in high overall thermal conductivity of straw bale walls. As the clear liner thermal bridges is shown at the adjacent are of straw bales and masonry brick in Figure 7.7. The external surface temperature of straw bales and bricks would be significant different.

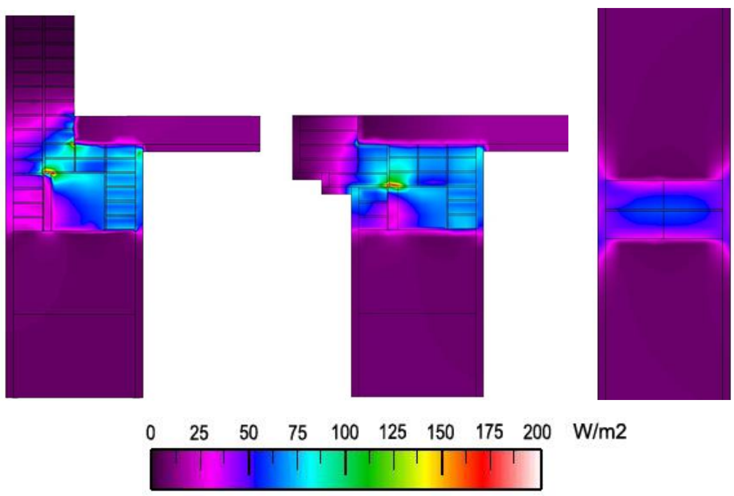


Figure 7.7. Thermal transmittance of the joint construction of sidewall (left), Joint construction of south and north wall (middle) and section of sidewall in the THERM simulation.

The different external surface temperature of structural elements and straw bales in the simulated situation can be used to estimate the potential for differential thermal expansion of the external surface (Figure 7.8 and Figure 7.9). According to the simulation, the greatest surface temperature difference occurs on the gable end section and the joint construction of the gable end. The temperature can reach -23 ℃ on surface of masonry bricks (Figure 7.9). The simulation results explain the linear cracks on gable ends. The large surface temperature differences can lead to differential temperature expansion issues within external surface render. Cracks are likely to occur and can have serious consequences, including the ingress of water into the underlying straw bales.

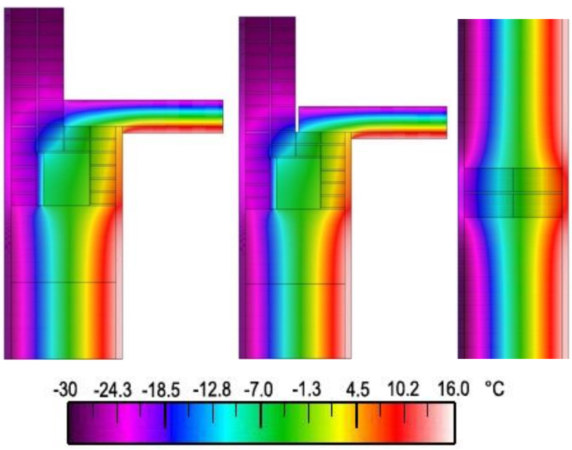


Figure 7.8. Temperature distribution of design joint construction of gable end (left), realistic joint construction of gable end (middle) and gable end section (right).

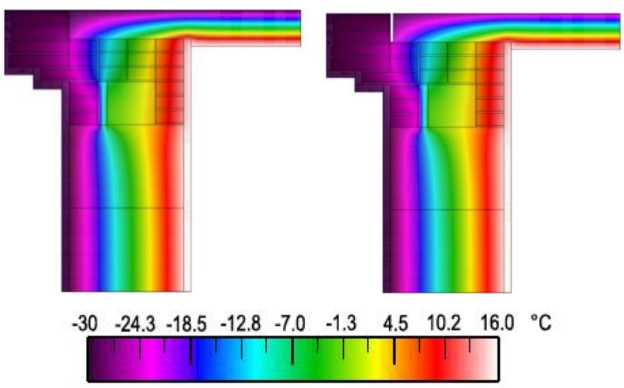


Figure 7.9. Temperature distribution of design joint construction of south and north wall (left), realistic joint construction of south and north wall (right)

The situation for the south and north walls is different. Regardless of clear thermal bridging identified in the image of thermal transmittance, there is no significant surface temperature variation on the south north walls in the simulation. The surface temperature was similar in both design joint construction and realistic joint construction (Figure 7.9). This is likely to be as a result of the decorative overhang brick construction at the eaves. The additional thickness of brick provides additional thermal resistance to the non-straw bale elements and decreases the variation of the surface temperature. The external surface temperature distribution only initiates differential expansion causing cracking to appear on the gable ends.

The condensation and frost issue observed internally can be explained by examining internal surface temperature of the simulated constructions. The lowest internal surface temperature appears on internal surface of the joint construction of the gable ends. The internal surface temperature on the internal corner is significantly lower than the room temperature. Failure to correctly install insulation material will lead to a surface temperature more than 3.0℃ lower than if the joint had been installed as per the design specification. The thermal transmittance image indicates that the linear area between EPS board and bricks can result in a significant thermal bridge when a gap is present (Figure 7.9). The gap between the insulation material and the brick work can result in the surface temperature on the internal corner being lower than freezing point (Figure 7.10).

Figure 7.10. Frost issue on internal corner (left) and simulation result of the realistic joint construction within allowable range of error (right).

7.3. Analysis of the experimental building

This section analyses two influences of the walling construction on the vapour movement within straw bale walls. The analysis of the experimental building is based on the yearly monitoring data.

7.3.1. Analysis of the monitoring data

There are four major findings in the monitoring data which are the overestimation of RH levels, different duration of 100% RH in the monitoring positions, the different RH distribution within different walling facing and the different rate of daily RH/T variation within different walls.

a. Over estimation of RH levels

During the winter season of the period of the monitoring research, the sensors showed 100% RH for long durations of the monitoring positions. There are two features of the 100% RH situation:

1. Instant change of RH between 94%-100% at the internal positions from December 2016 to March 2017.

2. Monitoring of constantly 100% RH at the external position from October 2016 to January 2017. The constant 100% RH was changed to 81% to 84% during the temporary heating process and the RH levels fluctuated from 94% to 100% from February 2017 to March 2017.

For the first case of the instant change, it is likely that the sensors of the monitoring positions did not work properly in high RH environment during winter months. The recorded RH data show instant change from 94% RH to 100% RH and 100% RH to 94% RH from two consecutive data collecting points. The instant RH change between two data collection points are recorded occasionally at the beginning of winter seasons. As there is no artificial method of change in the environmental RH during the monitoring research, the RH change would not be rapidly between two data collecting points. As there were no significant hourly fluctuation of air humidity levels and air temperature at the beginning of winter months in 2016, the instant change of

RH levels are likely to be a faulty recording by the sensors within straw bale walls. As a result, the monitored 100% RH should be in the range of 94% RH to 100% RH.

Secondly, the 100% RH could also be an effect of condensation. The RH data of the external sensor of the location No.6 show fluctuating result of the RH level from 94% to 100% from November to December (Figure 7.11). The periods of RH levels jump from 94%-100% are similar to the period that monitored temperatures fluctuate around freezing point. The RH data maintained 100% RH after the fluctuation period of time and dropped to 93%-95% RH during the heating process of the building. The RH data maintained 100% after the heating process and decrease to 95.9% on 13th March 2017. The mechanism of the RH sensor is to measure electric resistance between two sensor nodes, measuring pure ice can give faulty result of 100% RH to the sensor. The results of the fluctuating temperature around freezing point may include condensation ice within straw bale walls. Because the heating process of the internal space warmed up the walls above freezing point and melted the condensation ice, the RH readings were back to the actual RH within straw bale walls. The RH readings were back to 100% RH when the monitoring temperatures were lower than 0℃ after the heating process. As a result, the real RH situation could have been overestimated.

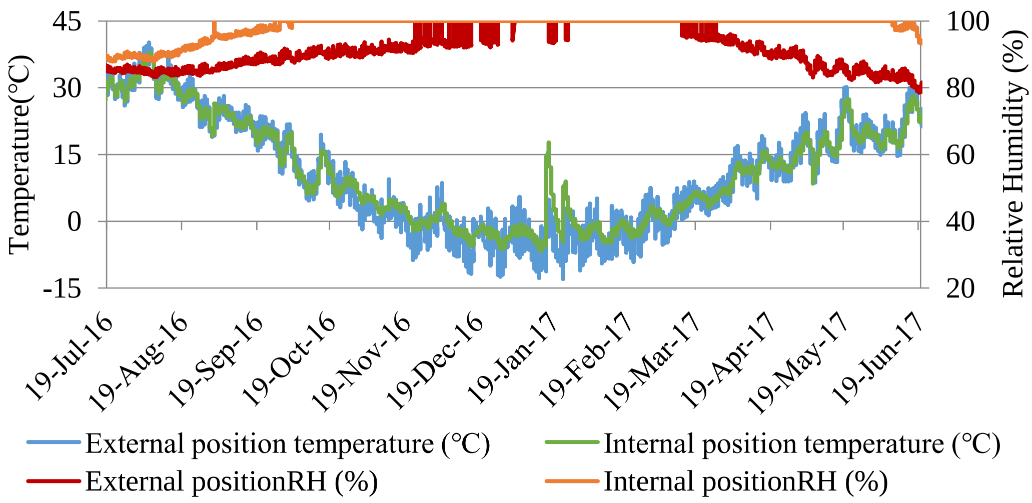


Figure 7.11. Monitoring data of relative humidity and temperature of the location No.6

Bronsema (2010) demonstrated in a similar climate region the problem of using electronic RH sensor during first year monitoring. Considering high atmospheric RH (80%-90%) and low atmospheric temperature (-10℃ to -20℃) in winter time in local area in this research, the use of electronic RH/T sensor may not function properly during winter time. Further research may benefit from use calibrated wood stick probe (Carfrae *et al.*, 2011) to estimate the moisture content of straw bales within walls in northern China.

b. Duration of 100% RH

Following the initial decrease of the RH in the first three weeks, the humidity levels of most of the monitored positions keep increasing to 100% RH and the RH levels stay the same until spring next year (7.12 & Figure 7.13). The monitored 100% RH level do not appear at the same time between the inner sensor locations and the external sensor locations. For the monitoring positions in the South facing walls and the east gable end wall, inner monitoring locations have longer duration of the 100% RH situations (Figure 7.11). Whereas the situations in the west gable end wall and the north facing walls are different (Figure 7.12). The outer sensor locations have recorded longer 100% RH situation than the inner monitoring locations.

Even though the 100% RH have been recorded in each monitoring locations, the situation are not identified in all sensor positions. For most of the monitoring locations, the 100% monitoring data are recorded in both the inner sensor position and the outer sensor position. Some monitoring locations (location No.7, location No.4, location No.19 and location No.6) have recorded the 100% RH appear in one sensor position and there is no 100% RH situation appeared in the location 18 during the whole monitoring period (Figure 7.13).

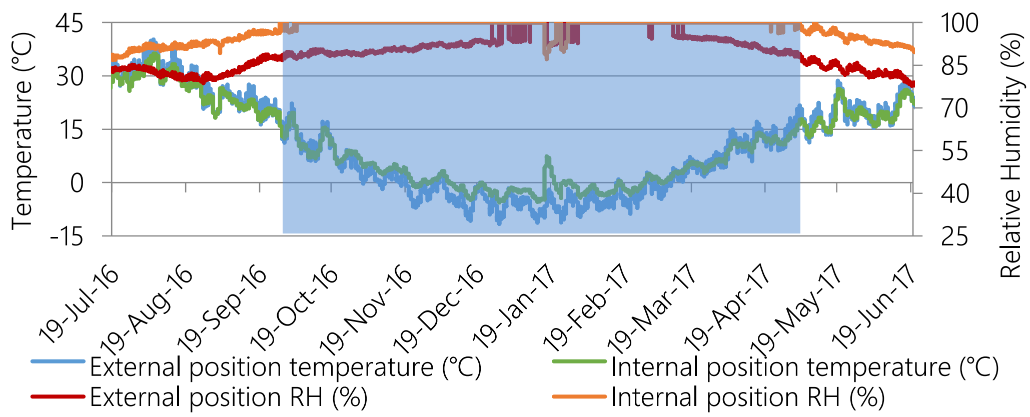


Figure 7.12. Indication of long period of time of 100% RH (blue rectangle) in the monitoring position No. 12.

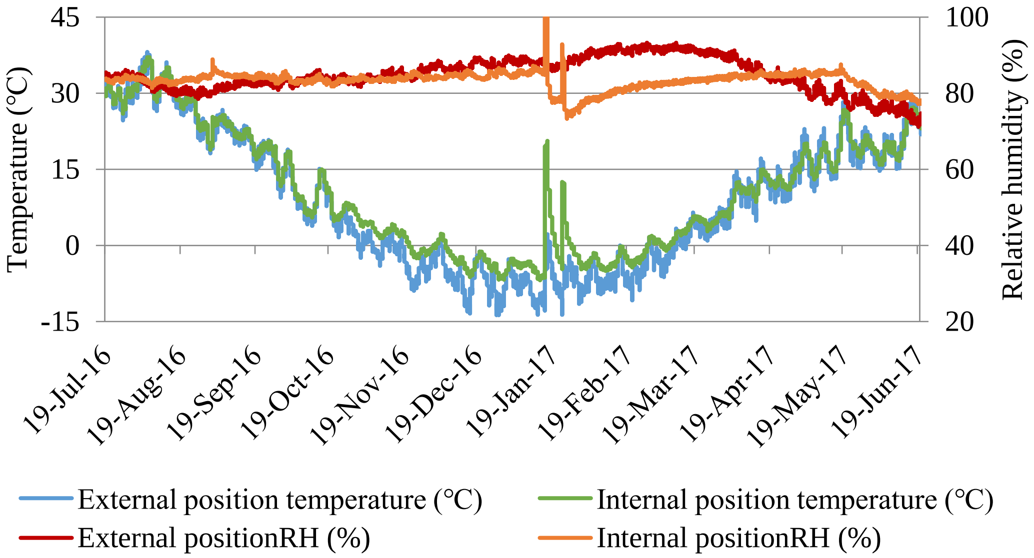


Figure 7.13. No duration of 100% RH issue in the location No.18.

c. RH distribution in monitoring position through walling section

The RH distributions through the wall section of north facing walls are directly opposite from the ones in the south face walls (Figure 7.14), the east gable wall (Figure 7.15) and the west gable wall (Figure 7.16). The monitoring locations inside the south facing walls, the east gable end wall and the west gable end wall have recorded that the RH levels of internal sensor positions are constantly higher than the RH levels of the external sensor positions. Despite the similar initial RH readings of internal sensor location and the external sensor position in the location No.1, the monitored RH levels of inner sensor position are constantly 3-5% lower than the ones of external sensor location during the whole monitoring period (Figure 7.15). Whereas the RH distributions in north facing walls are significantly different from the ones in the other wall facing. External sensors of the positions inside north face walls show that the RH levels increases faster than internal positions and the RH levels are constantly higher than internal sensor locations (Figure 7.16).

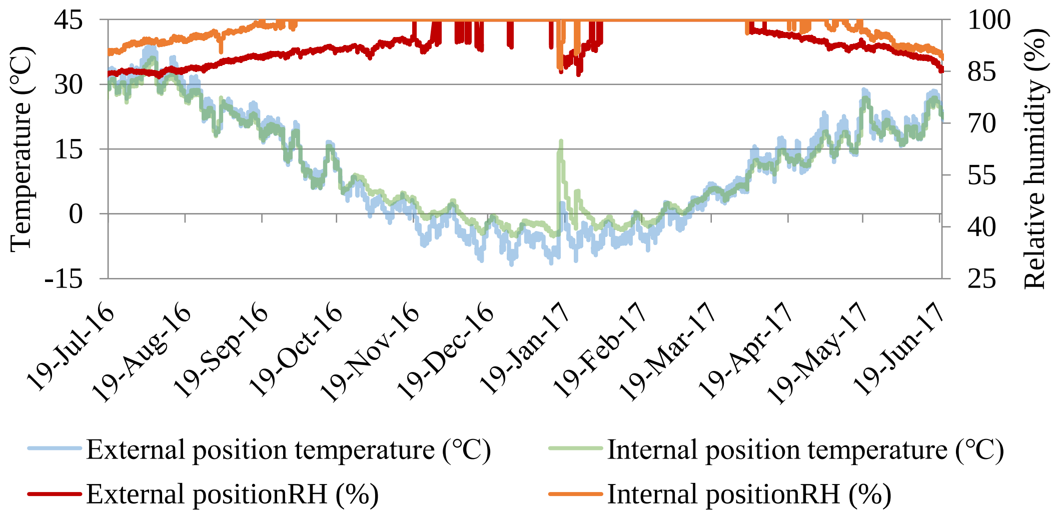


Figure 7.14. Monitoring data of relative humidity and temperature of location 13.

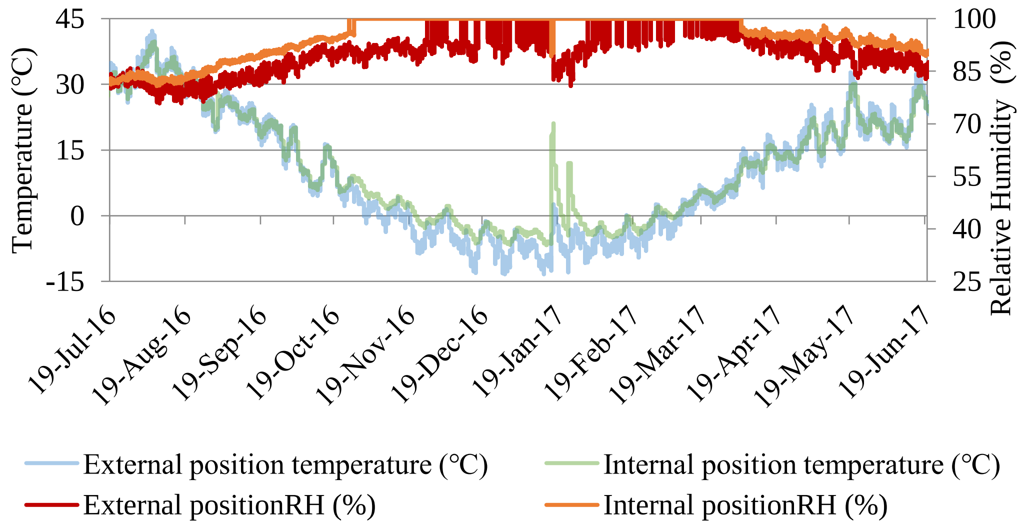


Figure 7.15. Monitoring data of relative humidity and temperature of location No.1.

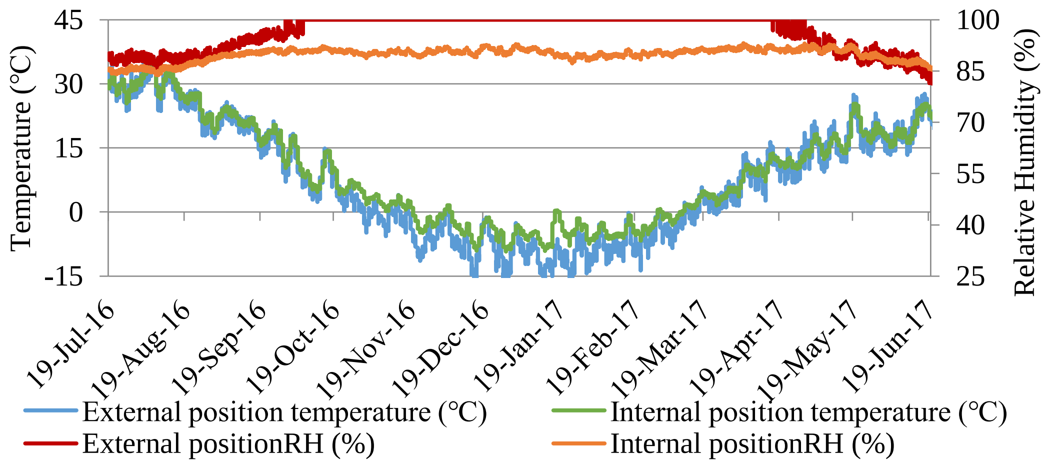


Figure 7.16. Monitoring data of relative humidity and temperature of the location No. 19.

The differences of RH distribution through walling sections with on-edge bales (Figure 7.17) are not as significant as the ones with laid-flat bales (Figure 7.18). The relative similar RH/T results of the location No.12 present the systemic error identified in previous section. As the sensors were plugged into bales during installation process of the monitoring devices, the actual locations of monitoring sensors would be different from the initial designed location of monitoring sensors. However, as the systemic error is only identified in one monitoring location, the error does not have significant impact on the monitoring research.

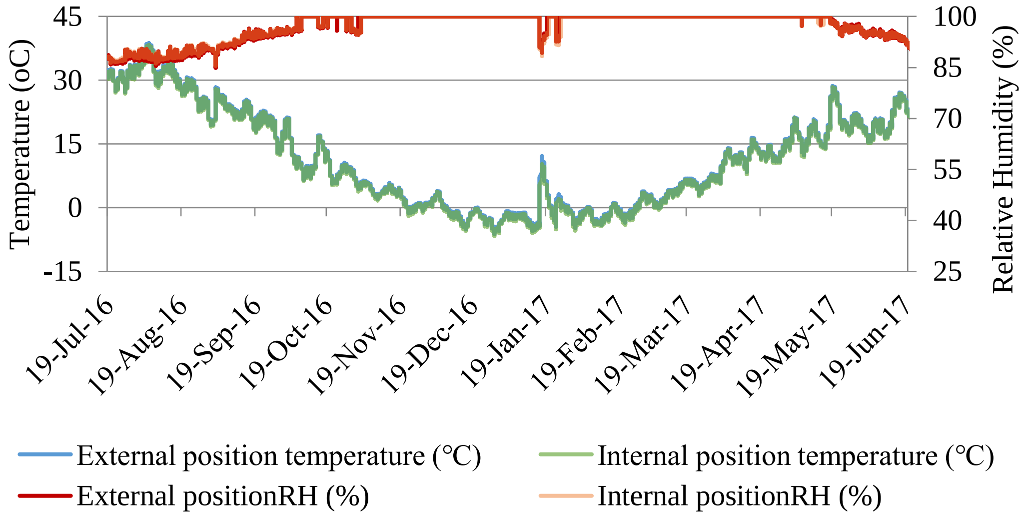


Figure 7.17. Systematic error identified in the location No.12.

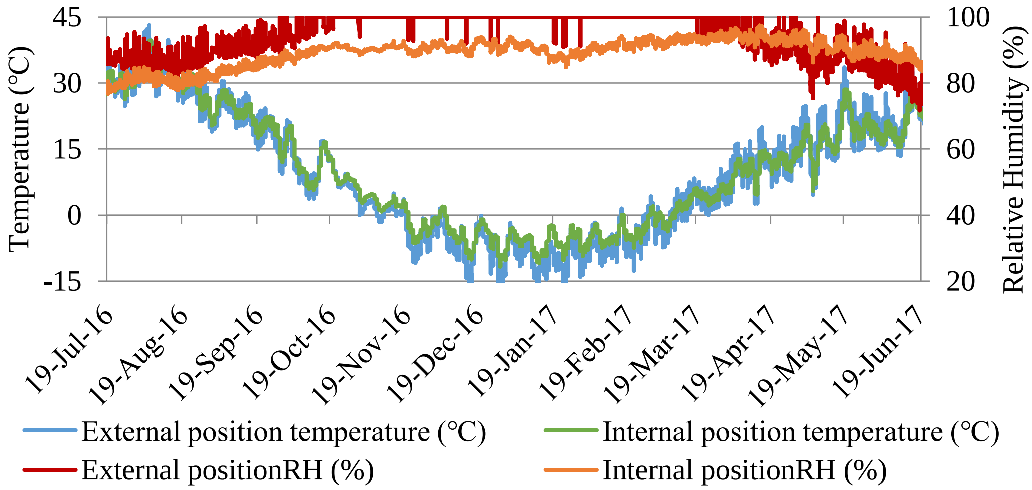


Figure 7.18. Monitoring data of relative humidity and temperature of location No.4.

d. Diurnal RH/T fluctuation of sensor locations

Due to the inaccuracy of monitoring data in winter months, the comparisons of RH fluctuation are divided into before winter months (19th July 2016–19th October 2016) and after winter months (19th March/2017-19th June 2017). The largest variations of daily RH/T difference are recorded in the low monitoring locations inside south facing walls.

As the south facing walls have largest solar gain, the internal temperature of straw bale walls increase much more than the other facing walls on diurnal basis. Considering the daily lowest temperatures of monitoring locations are largely affect by the lowest air temperatures which are broadly to all faces of walls, the greatest daily temperature differences were recorded in the south facing walls (Figure 7.19 & Figure 7.20). However, due to the overhang design in the experimental building prevent the high monitoring positions to receive solar radiation (Figure 7.21), the high monitoring locations did not record large daily temperature fluctuation as the low monitoring location did. Since the actual water presence within straw bales would not have as rapid change as the temperatures, the diurnal fluctuation of relative humidity would broadly be an effect of the diurnal temperature fluctuations.

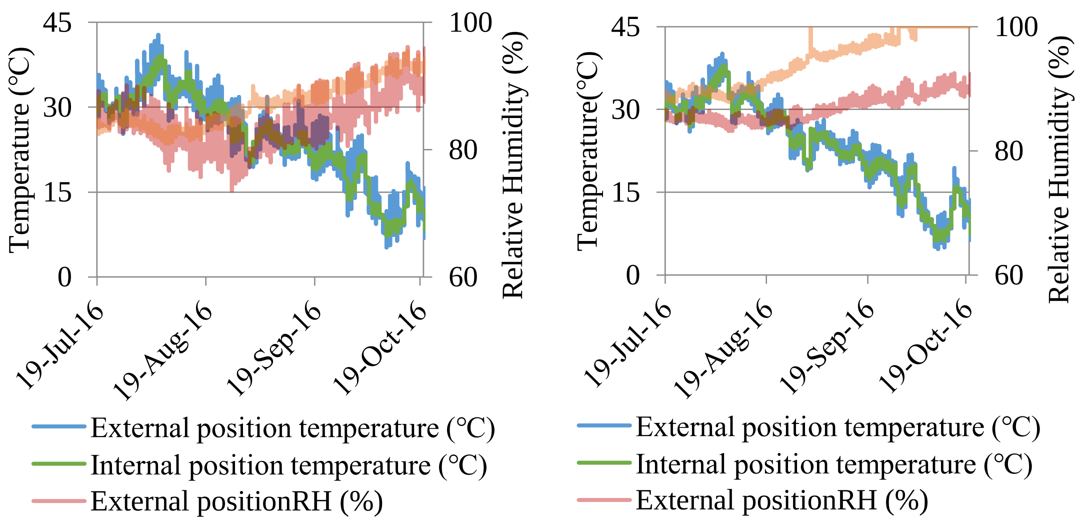


Figure 7.19. Monitoring data of temperature of location No.6 (left) and location No.7 (right) from 19th July 2016–19th October 2016.

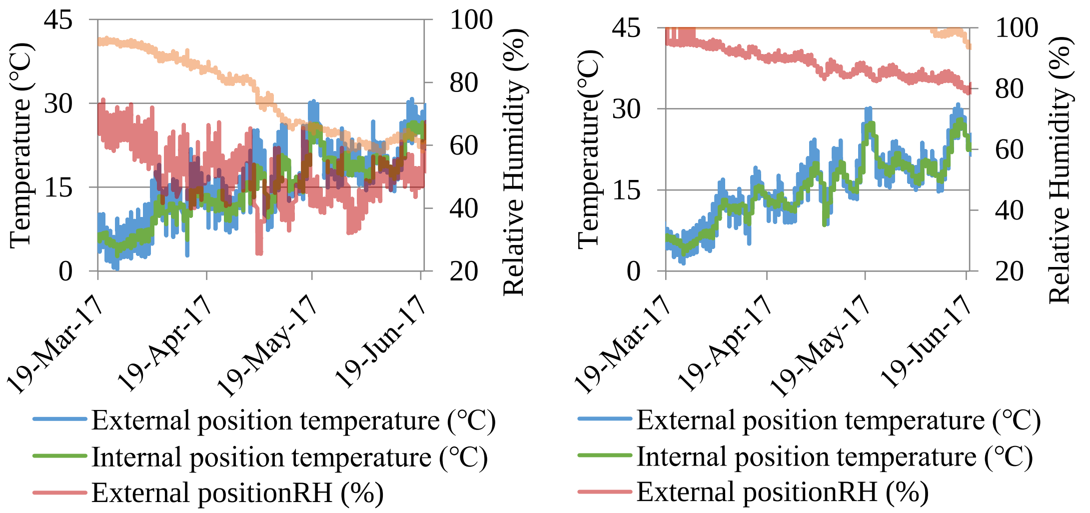


Figure 7.20. Monitoring data of temperature of location No.6 (left) and location No.7 (right) from 19th March/2017-19th June 2017.

Figure 7.21. Effectiveness of roofing design in preventing direct solar radiation (left) on high monitoring positions (right) inside south facing walls .

For the same reason, the RH levels have larger fluctuation in the west gable end wall than the east gable end wall of the experimental building due to exposure to west sun radiation (Figure 7.22 & Figure 7.23). The most daily difference of RH level was 4.7% RH at the external sensor position of location No.1 in 1st August 2016 and the mean daily RH difference was 3.7% RH of the external sensor in the months before winter. The most daily RH difference and mean daily RH difference are 5.2% and 3.4% RH in the months after winter. Comparing with the daily RH difference at the external sensor positions of location No.1, the daily RH difference was lower at the external sensor positions of location 13. The most daily RH difference and mean RH difference are less than 1% RH at the external sensor location of the No. 13 in both before winter months and after winter months.

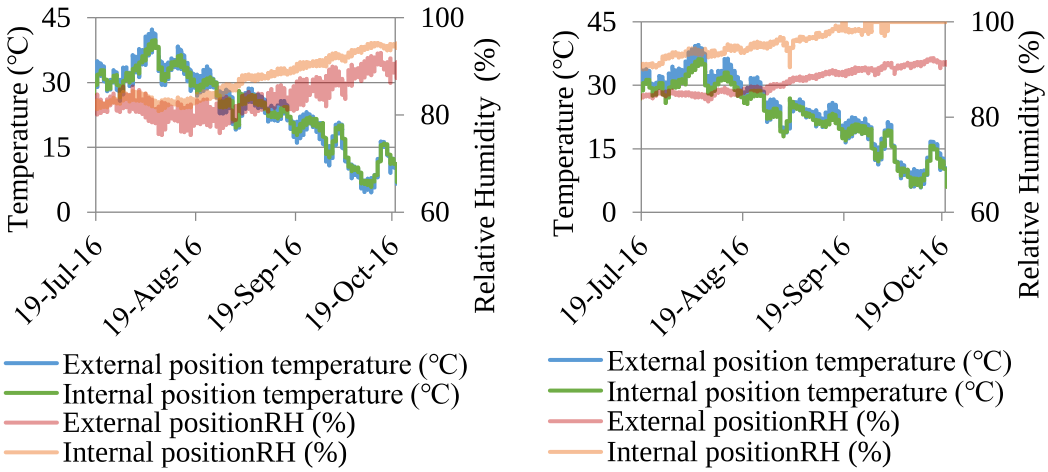


Figure 7.22. Monitoring data of temperature of location No.1 (left) and location No.13 (right) from 19th July 2016–19th October 2016.

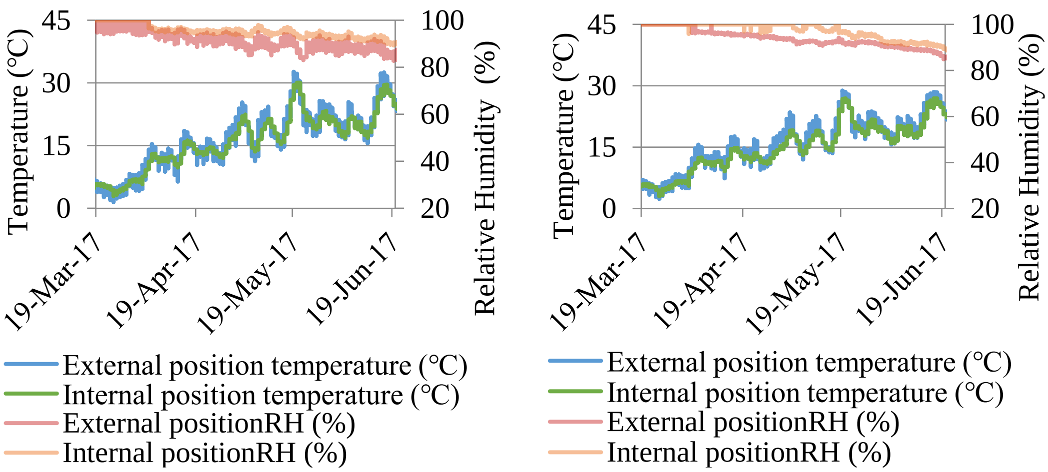


Figure 7.23. Monitoring data of temperature of location No.1 (left) and location No.13 (right) from 19th March/2017-19th June 2017.

7.3.2. Influence of construction detailing on the monitoring data

Both the RH/T data of the monitoring locations and the actual vapour pressure of straw bale walls show significant influences of building orientation and bale stacking on the vapour movement of straw bale walls in the experimental building.

a. Building orientation

The orientations of the experimental building have notable impact on the RH/T changes and drying trend of the straw bale walls during the monitoring research. The wind intensities and wind directions have significant influences on the RH/T changes and drying trend of straw bale walls regarding different building orientation.

Due to different wind intensity in the local area, the relative humidity levels of straw bales are different in each orientation wall. The yearly data of wind direction and wind speed (Figure 7.24) suggest that the wind is stronger and more rapid from south and south south-west (Meteoblue, 2017). The east gable end wall received lest annual wind intensity than the other wall facing.

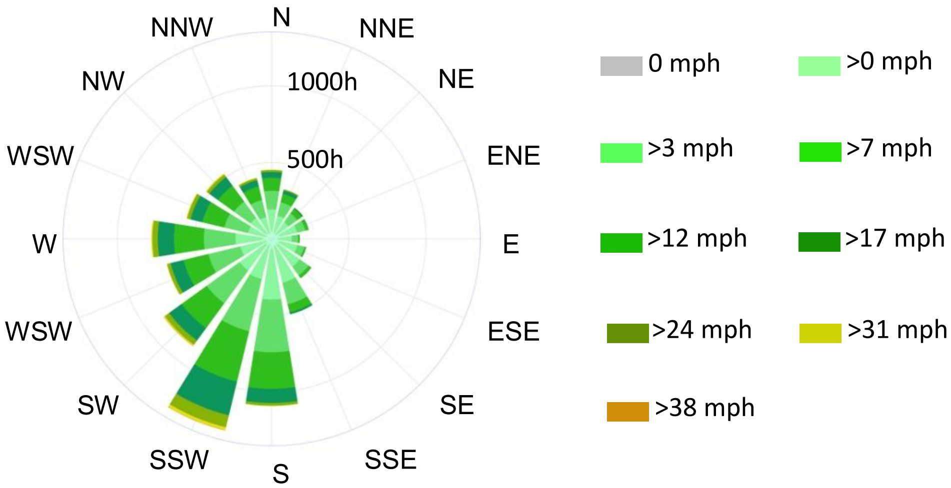


Figure 7.24. Annual wind intensity plot of Changchun. (Meteoblue, 2017)

The more intense annual wind leads to quicker drying trend of straw bale walls. The driving wind speed up drying process of external render and results in lowest RH levels of south face walls than other faces walls. Comparing the monitoring data from the No.5 and the No.19, the monitoring location of the south facing wall has much lower monitoring RH levels after initial RH increase.

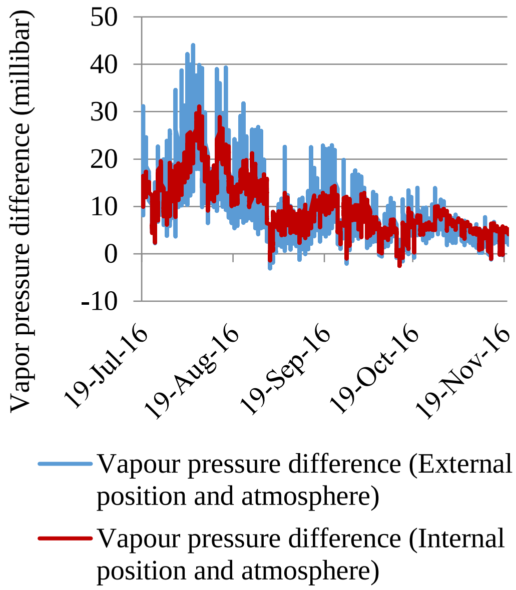
The north facing wall does not have lowest wind intensity in comparison with other walling facing. However, the highest RH levels were recorded in the monitoring locations inside north facing walls. There are two possible explanations for the different distribution of RH across section of the north facing walls than the other three faces of walls: Firstly, the wind comes from south face of the building, the lowest wind velocity would be outside north face of walls. The north face of walls may not have sufficient driving wind to dry the lime rendering; Secondly, the dominating wind in the winter time is northerly (Guoyu *et al.*, 2005). During that time, the temperature is lower than freezing point and vapour is likely to become ice during the time. The wind may not significantly take vapour from north face walls. As a result, the highest RH levels are maintained in the north face walls rather than the east gable-end walls and the drying trends of the straw bale walls are limited by the more rapid winter season wind from north.

The greater daily mean RH variation of the monitoring positions has close connection with the annual wind intensity of the construction site. According to the monitoring data, the most daily RH variation were monitored in the south facing walls during the monitoring research which is the same direction of most wind intensity in Changchun. Lower daily RH variations in other facing walls map the lower annual wind intensity in the construction site. Because more rapid wind can both bring more moisture into the walls and dry out the moisture within the walls, the more rapid wind lead to more daily variation of RH levels in the straw bale walls in the experimental building. However, as explained in section 2.3, high RH levels and high temperatures create desirable environment for straw degradation, the straw bales inside south facing walls and west gable end wall may have greater potential of degradation than the ones in the other facing walls.

b. Bale stacking method

Compared with on-edge stacking bale wall, the laid-flat bale wall have greater vapour pressure gradient between the exterior sensor location and the atmosphere than the one located in the same sensor location in the laid on-edge bales (Figure 7.25) from the beginning of the monitoring research to the winter months. Due to the drying process of the walling constructions is not finished during the period of time; the higher gradient indicates that the laid-flat bales adsorb more moisture from rendering construction than the laid on-edge bales. However the south facing wall with laid flat bales have established the moisture content exchange quicker than the laid on-edge bales and therefore indicates shorter drying period of straw bale wall than the wall with laid on-edge bales (Figure 6.27 & Figure 6.28).

As shown in Section 4.2, the moisture adsorption and desorption process of straw bales is mainly through the cross section of straw. Therefore the straw bales with laid-flat stacking method adsorb more moisture than the laid-on edge bales during the drying process of rendering construction. For the same reason the laid-flat bales have quicker response to low air humidity levels in dry months and result in faster drying process of the laid-flat bales within the south facing walls.



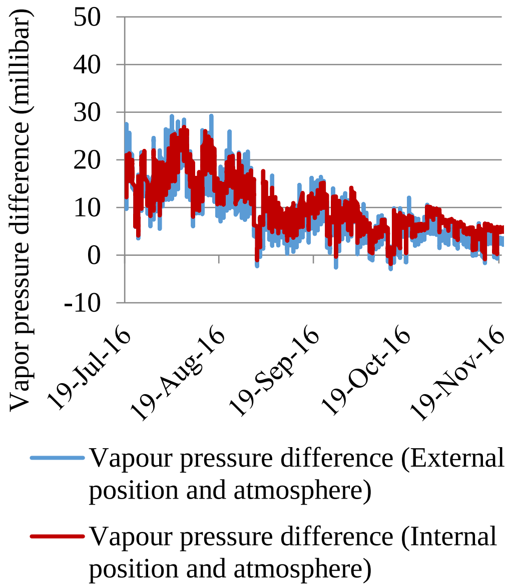


Figure 7.25. Vapour pressure difference of the location No.7 (left) and the location No.10 (right) from 19th July 2016 to 19th November 2016.

There is no notable influence of stacking method on drying trend of north facing straw bale walls. However, the stacking methods of straw bales have significant influence on monitoring temperature within straw bale walls. To exclude influence of solar radiation on temperature distribution within straw bales, the high monitoring locations on north facing walls are analysed.

The monitoring temperatures in the laid-flat bale walls are notable lower than the monitoring temperatures in the laid-on-edge straw bale walls (Figure 7.26). As there is no regular heating system in the experimental building and all the doors on partitions were never installed, temperatures of the internal space were exactly the same during the weekly inspections of the experimental building. As a result, higher temperature inside the laid on-edge bale walls are the results of higher thermal conductivity of the straw bale wall with on-edge stacking. Even though the on-edge bales have notable lower thermal conductivity property than the flat bales (McCabe, 1993; Strohballenbau, 2009), the lower thermal transmittance of on-edge bales than flat bales may not be as significant as the reduced thickness of straw bale walls. The application of on-edge stacking bales in straw bale buildings may not achieve lower thermal conductivity properties of straw bale walls than the laid flat bale walls.

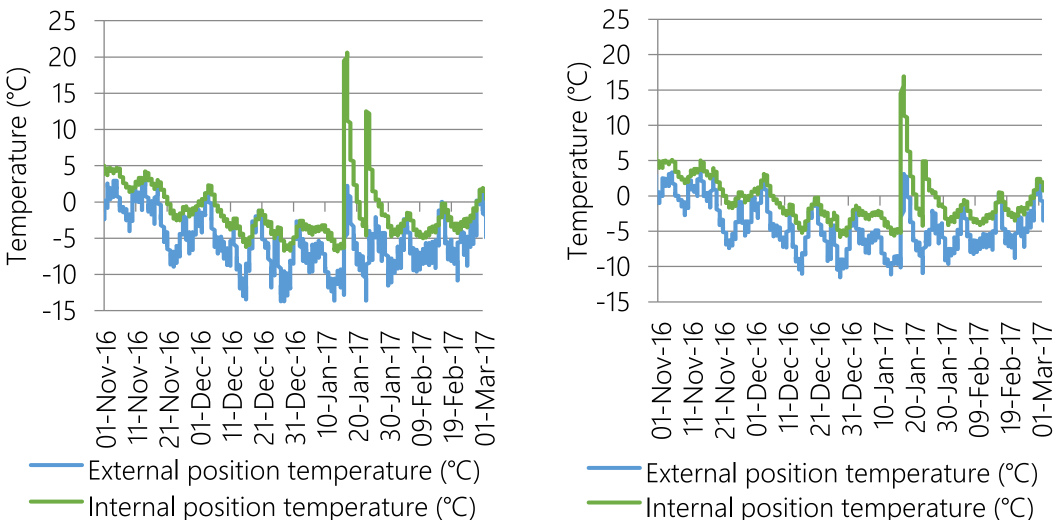


Figure 7.26. Monitoring temperature data of the location 18 (left) and the location 16 during winter months.

However, application of laid-on-edge stacking in straw bale walls may increase temperature buffering properties of straw bale building. As shown in the Figure 7.18, quicker response of temperature change are monitored in the laid-flat straw bale wall than the laid on-edge bale wall. Comparing the two stacking method of bales with similar walling thickness would result in similar thermal conductivities of the two stacking method and higher thermal buffering properties of laid on-edge bales. As higher buffering properties of walls can result in higher thermal comfort and higher energy efficiency of buildings in the areas with large daily temperature difference. As the weathering conditions of northwest China features the high daily temperature variation (Liu *et al.*, 2010), the straw bale buildings can benefit from the laid on-edge stacking method of straw bales in the northwest China.

c. Walling construction

The comparison of the monitoring results of location No.20 (Figure 7.27) and the location No.19 (Figure 7.23) justify the RH distribution at similar height with different building constructions in the same direction of wall. As the RH reading of the external sensor location of the 450NU showed continuously 100% RH level from 26th September 2016 to the end of the monitoring research, the external sensor of the 450NU is considered faulty and the monitoring data will not be analysed after 26th September 2016. In comparison with the monitoring data ofNo.20, the RH levels of

450NL are minor lower from 1st/September2016 during the monitoring research.

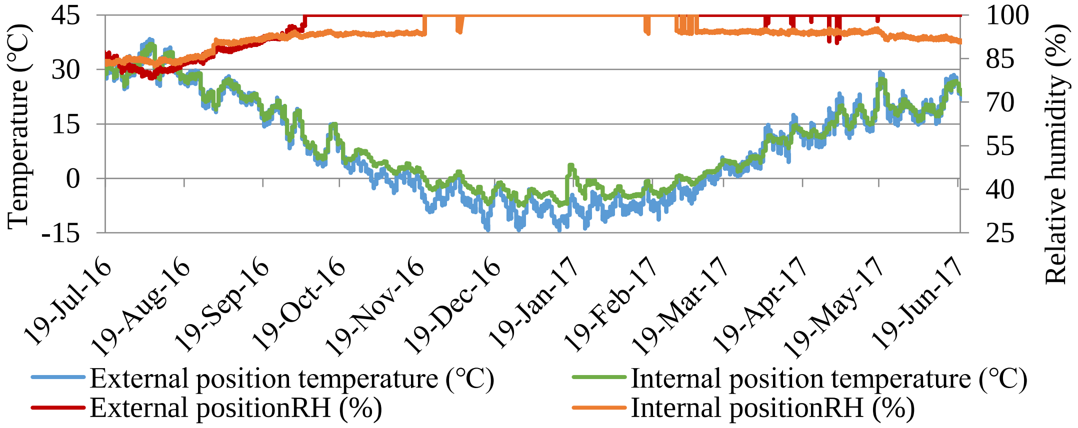


Figure 7.27. Monitoring data of location No.20.

The different walling construction detailing of the straw bale walls around location No.19 and location No.20 may be the reason of the different RH distribution during the monitoring period. The constructions of the under window areas of straw bale walls connect window sill and the insulation layers of the window sill (Figure 7.28). Such constructions involve more detailing construction than the straight walling construction around the No.19. The complex construction detailing may increase the potential of issues of construction quality and leakage. , the RH levels of the environment of the under window areas are higher than the RH levels at the lower positions of straight walls during the monitoring period in this research hyperthetically. As high relative humidity levels indicate h high moisture content of straw bales, the straw under the windows would have high risks of degradation. As a result, methods to reduce potential water intrusion of the under window area are needed in further design of straw bale buildings.

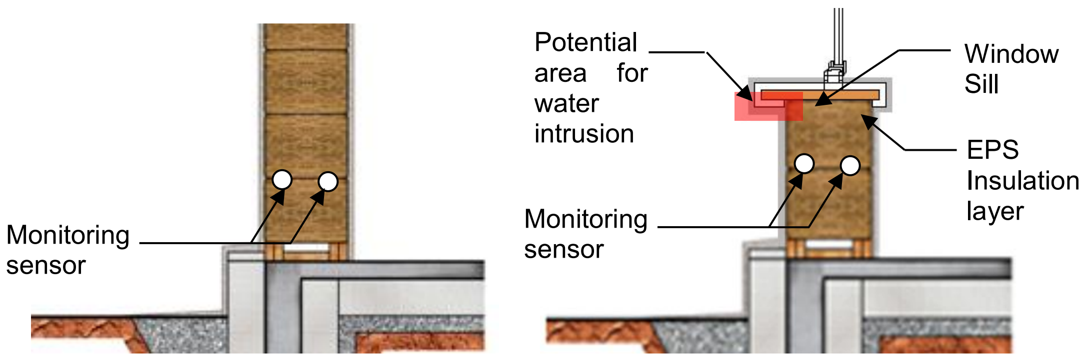


Figure 7.28. Walling construction of the straight walling (left) and the walling around window opening (right).

7.4. Evaluation of susceptibility to degradation of straw bale building

As discussed in section 7.2, the existing models for straw degradation are problematic in predicting susceptibility to degradation of straw inside walls. This section initial discusses the critical environment for straw degradation which takes into account of the modified models and the building inspection results from the onsite visits. The susceptibility to degradation of straw inside the experimental building is evaluated by applying the modified model in analysis of the monitoring data as follow. Based on understanding of susceptibility of degradation of straw in the previous sections, proposed designs of straw bale building are discussed in context with climatic feature of northern China.

7.4.1. Analysis of the suitability of existing predicting models in context with climatic features of northern China

Based on the understanding gained in the chapter 4 and chapter 6, this section discusses and analyses the suitability of both the existing isothermal model and the modified isothermal model. Suitability of the degradation isopleth model is discussed in context with reasons for the inaccurate predictions and suitability of the model as follow.

a. Suitability of the modified isothermal model

The calculated moisture content of straw by using modified isothermal model is compared to the actual moisture content measured by the moisture content meter (Table 7.2). There is no statistical differences between the actual moisture content and the calculated moisture content from the modified isothermal model. Comparison of the modified isothermal model and the isothermal model of Lawrence et al. (2009b), the modified model can produce closer prediction of the real moisture content of straw within walls in the experimental building (Figure 7.29).

Table 7.2. Actual moisture content and calculated moisture content from modified isothermal model and the Lawrence et al. (2009b) equation.

Monitoring location	Monitored moisture content		Monitored RH from sensors	Calculated Moisture content (Modified Model)	Calculated Moisture content (Lawrence et al. (2009b) equation)
No.1	Inner	20.3 %	85.1 %	19.4%	23.6%
	Outer	28.0 %	90.5 %	26.6%	32.1%
No.4	Inner	15.3 %	74.9 %	13.5%	16.4%
	Outer	24.0 %	85.7 %	20.0%	24.3%
No.9	Inner	12.8 %	65.5 %	10.5%	12.8%
	Outer	14.6 %	71.7 %	12.3%	15.0%
No.10	Inner	17.3 %	81.0 %	16.5%	20.0%
	Outer	21.0 %	83.7 %	18.3%	22.2%
No. 11	Inner	18.0 %	83.8 %	18.4%	22.3%
	Outer	23.0 %	86.8 %	21.1%	25.6%
No.12	Inner	28.6 %	91.9 %	29.8%	36.0%
	Outer	33.0 %	92.1 %	30.3%	36.7%
No.18	Inner	17.0 %	77.8 %	14.7%	17.9%
	Outer	14.0 %	72.7 %	12.6%	15.4%
No.19	Inner	24.0 %	86.0 %	20.3%	24.7%
	Outer	16.0 %	82.6 %	17.5%	21.2%

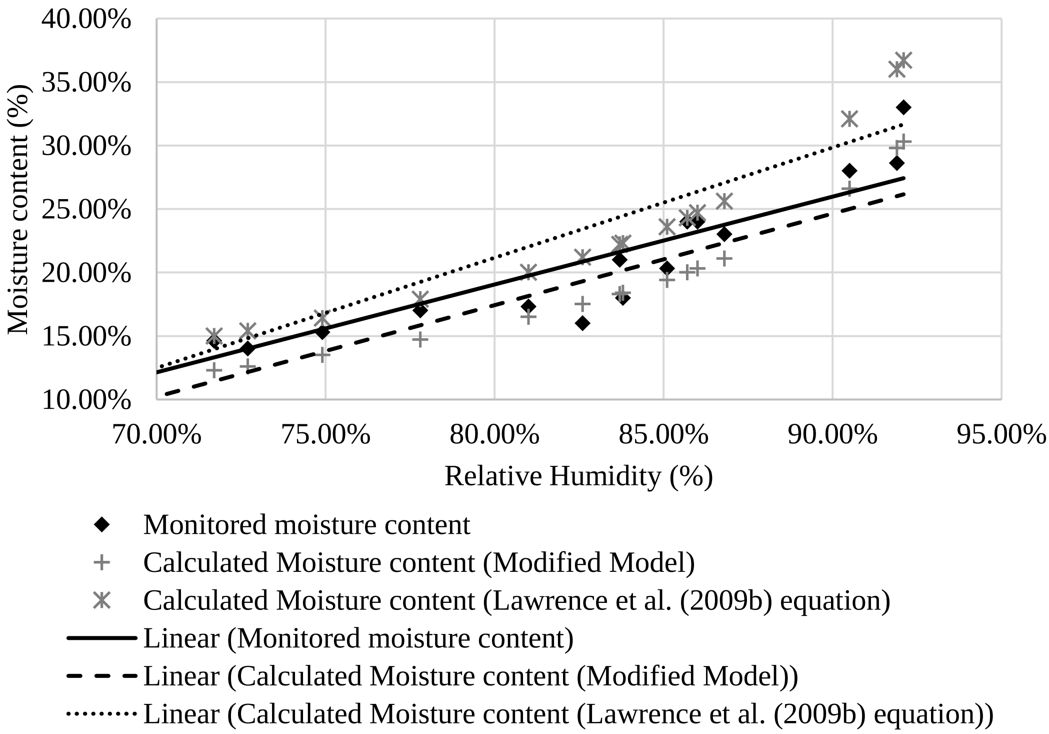


Figure 7.29. Comparison of calculated moisture content from isothermal model and actual moisture content in the experimental building.

Comparing to the Lawrence et al. (2009b) equation, the modified isothermal model produce lower accuracy predictions of moisture content at the location No.4, No.18 and No.9. The 24 hours monitoring data of the location No.4 and the location No.1 show that the RH levels of the location No.4 have downward trend before the final RH levels of the monitoring position and the RH levels develop upward toward final RH levels in the No.1 (Figure 7.30). Therefore straw experienced desorption at the position of 450SWL and experienced adsorption during the period of time. As a result, the Lawrence et al. (2009b) equation produces more accurate prediction of moisture content of straw in the desorption process whereas the modified model can estimate the actual moisture content in the adsorption process in the experimental building. The monitoring results show that the proposed application methods of isothermal models maps the real situations in the experimental building.

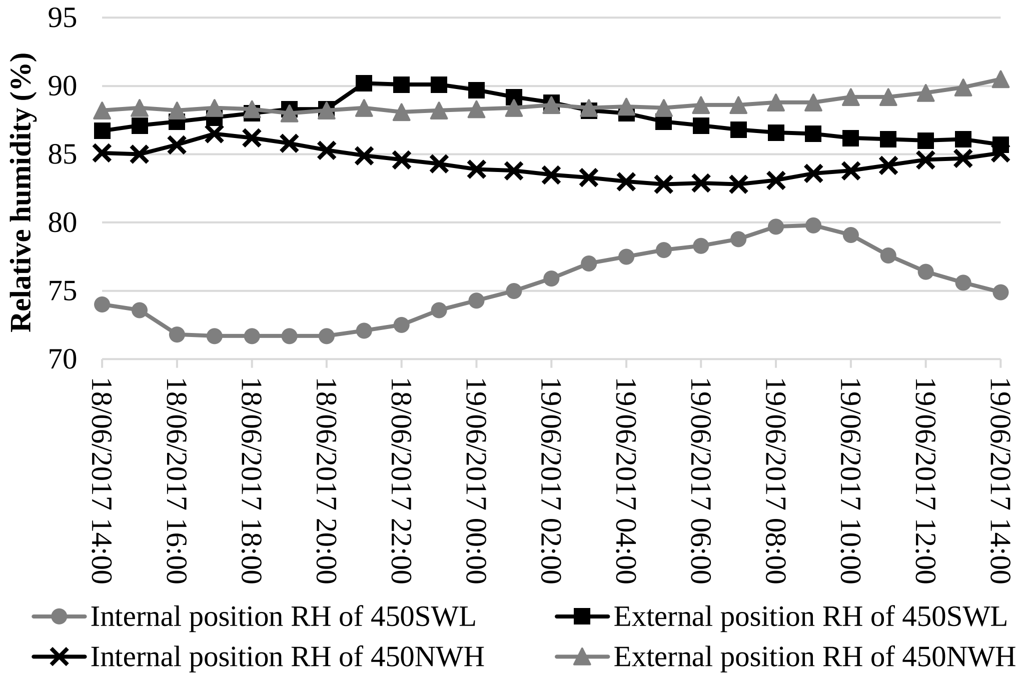


Figure 7.30. 24 hours Monitoring data of monitoring location of No.4 and of No.1.

Considering the accuracy of predicting moisture content of straw in the experimental building, this isothermal model can be further used in evaluating moisture content of straw inside straw bale walls in the climatic conditions of northern China. However, the isothermal model need calibration with moisture content sensor which is not part of this research.

b. Degradation isopleth model

The susceptibility to degradation of straw in the monitoring locations are analysed by applying the isopleth model. According to the isopleth model, the straw bales around the No.9 and No.19 would have experienced serious degradation during the monitoring period (Figure 7.31 and Figure 7.32). As the temperature range of the isopleth model is 0-30 °C, the monitoring data are not analysed with temperature lower than freezing point during winter months. The hygrothermal environment of location No. 9 are located in the ‘red area’ of the isopleth model from the beginning of the monitoring research to the beginning of June 2017 (Figure 7.31). Susceptibility to degradation of straw classified in the ‘yellow area’ in the isopleth model and becomes less concerns in the following month. The situations of the location No.19 are worse than the ones in location No.9, the ‘red area’ in the isopleth model are identified throughout the whole monitoring period (Figure 7.32).

Unlike the predicted straw degradation in the isopleth model, the opening up of the render layer outside the two monitoring locations show insignificant straw degradations. During the second onsite visit, the straw outside the monitoring location No.9 show insignificant decolourisation and no notable mould growth are identified on the straw surface by visual inspection through the drilled opining outside the monitoring location (Figure 7.33). Even though straw degradation is identified behind the render layer outside the monitoring location No.19, the situations are not as severe as the prediction of the isopleth model. The limited straw degradation only appear on the surface of straw bale stacking and the straw remain unchanged inside the bales. As the on-site visit show insignificant degradation of straw inside straw bale walls which is notably different from the prediction of straw degradation in the isopleth model in section 2.4.1 the suitability of the model to predict straw degradation is in question.

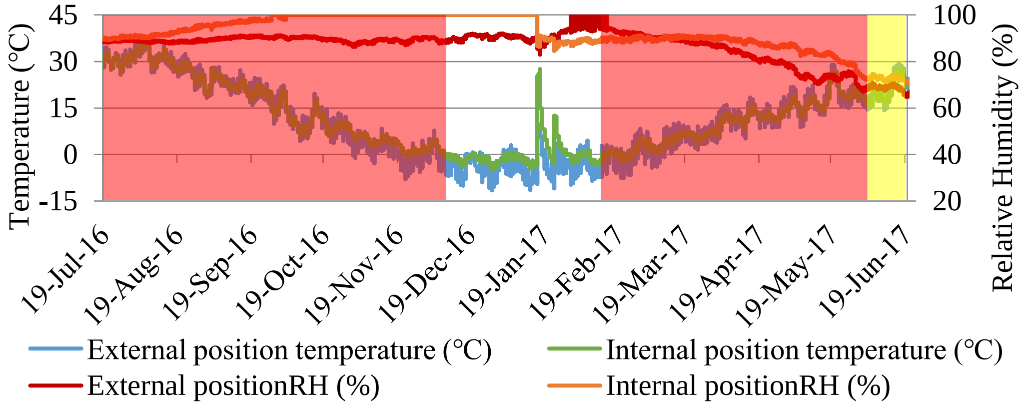


Figure 7.31. Susceptibility to degradation of straw around the monitoring location No.9 in the isopleth model.

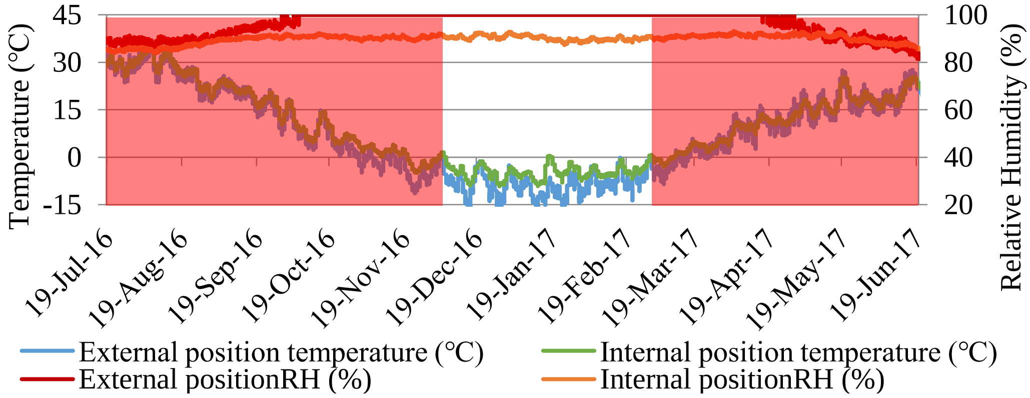


Figure 7.32. Susceptibility to degradation of straw around the monitoring location No.19 in the isopleth model.

Figure 7.33. Opening up outside the monitoring location No.9.

The overestimation of straw degradation by using degradation isopleth has been discussed in other research (Thomson and Walker, 2014), however, there is no proper explanations for the inaccurate prediction of isopleth (Thomson and Walker, 2014). As discussed in section 4.3 and the section 6.5.2 the presence of lime render significantly increase durability of straw both in the laboratorial experiment and the on-site visit. Even though there is limited scientific evidence on the connection of anaerobic decomposition of straw and the material of rendering constructions, application of lime based rendering constructions may have effects on limiting anaerobic decomposition of straw in straw bale walls. During the anaerobic digestion process, carbohydrates in straw is initially converted into sugars in the hydrolysis stage (Mussoline *et al.*, 2013). The sugar is later broken down to intermediates (acetic acid, hydrogen and carbo dioxide) by acidogenic and acetogenic bacteria (Mussoline *et al.*, 2013). The methanogenic bateria convert the intermediates into methane and carbon dioxide at the final stage of the anaerobic decomposition of straw (Mussoline *et al.*, 2013). The active PH range of the acidogenic and acetogenic bacteria is 6-10 and the methanogens has smaller range of allowable pH range (7.5-8) (Acharya, 1935).

With presence of lime based rendering constructions, reaction would be limited for two reasons: Firstly, the lime based rendering constructions would provide unfavourable environment for anaerobic decomposition of straw. The major content of lime is the calcium hydroxide which is a high alkaline pH standard (Bates *et al.*, 1956). The pH of calcium hydroxide is over 12 which is notably over the active range of the acidogenic and acetogenic bacteria. During the curing stage of lime based rendering constructions, calcium hydroxide provides long-term alkaline environment for straw within straw bale walls and therefore limit the decomposition of straw. In the second, the calcium hydroxide react with the intermediates of the anaerobic digestion of straw. Calcium hydroxide require carbon dioxide in the chemical reaction of achieving calcium carbonate during curing stage of lime based rendering and acetic acid is also neutralised by the high pH environment provided by the calcium hydroxide. As a result, the lime based rendering construction reduce the intermediates of the anaerobic decomposition of straw and increasing durability of straw bale walls. However, the effect of lime rendering on limiting anaerobic digestion are limited understood in current research (Wihan, 2007), the effectiveness of lime rendering in increasing durability of straw bale walls against anaerobic degradation remain uncertain.

The degradation between the lime render and the straw bales indicate the effect of aerobic degradation of straw and therefore the isopleth successfully predict the straw degradation. Due to breathability of the lime render, the oxygen condensation behind the lime render would not be as low as the one in the straw bales. As a result, the aerobic degradation happens at the area behind the lime render in straw bales. However, due to alkaline environment provided by the lime render, the degradation of straw is not serious with mix of lime render. The degradation of straw was identified 2-3cm behind the lime render.

Comparing the prediction of degradation (Figure 7.32) and the actual situation of straw (Figure 6.30) of location No.19, the serious degradation potential of straw maps the actual status of straw degradation at the adjacent area of straw bales and the lime render. The non-degraded situation of No.9 (Figure 7.31) is also shown in the Figure 7.33. Because of the oxygen inside straw bales are much lower than the adjacent area of lime render and the straw bales, the degradation does not penetrate into straw bales (Figure 7.34). However, if straw experiences serious degradation behind the lime render, hollows and cavity would likely form. Without support of straw behind lime render, the render may have cracking issues and lead to water penetration into straw bales. As a result, even though the degradation isopleth was not developed for predicting straw degradation inside straw bale walls, the isopleth is essential to evaluate straw degradation behind rendering construction whereas the internal status of straw bales can be evaluated by the moisture content of straw bales which is the key factor in the anaerobic degradation of straw which has been discussed in section 2.3.4 (Figure 7.35).

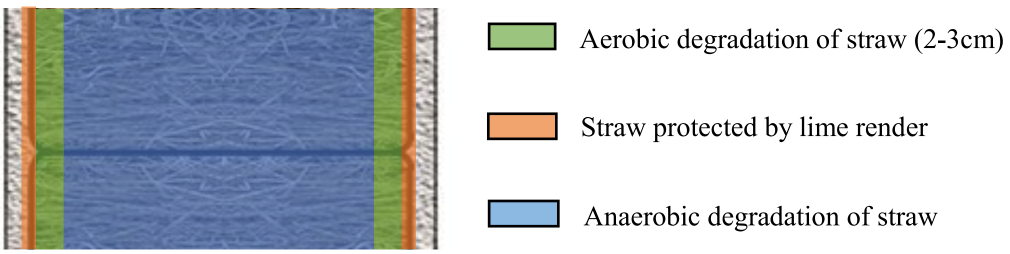


Figure 7.34. Analysis of straw degradation inside straw bale wall.

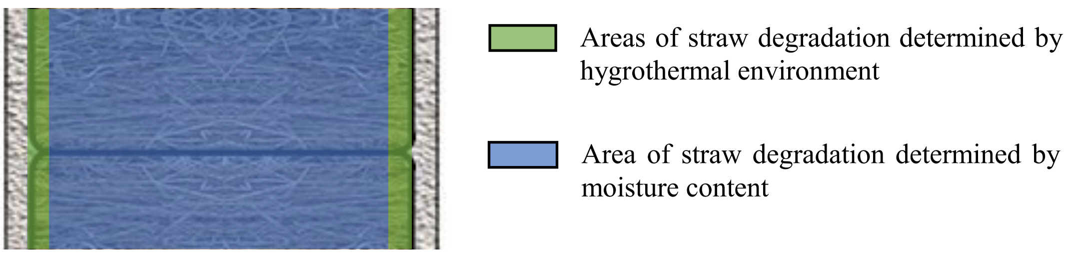


Figure 7.35. Critical factors for straw degradation inside straw bale walls.

7.4.2. Deciding the critical environment for straw degradation

As has been discussed in the section of 2.3 and 2.4, there are two key elements (moisture content and relative humidity and temperature of the environment) for straw degradation. The hypothesis of straw degradation in the experimental building is that straw would potentially have experienced greater degradation in high temperature and high RH situations. The triggering temperature of straw degradation is continuously above 0℃ for the period of 24h. The high temperature risk of straw degradation is over 30℃. Considering present of lime render in the experimental building, the straw may not have serious degradation at 75% RH and 30℃ in the experimental building. Concluding from the environment for supporting straw degradation, the trigging moisture content of straw degradation can be converted to surrounding RH by using the modified sorption isothermal model proposed in section 4.2.5. The critical RH for straw degradation is expected constant over 85% RH in the monitoring data of the experimental building in this research.

There is a labelling system to clarify the risks of straw degradation designed in this research. The situation of over 30℃ and over 85% RH would be considered dangerous situation for straw degradation in the analysis of the straw degradation potential and the RH/T data in this region will be labelled red. The situation of over 0℃ and over 85% RH would be considered have moderate risk of straw degradation and the RH/T in this regions will be labelled yellow in the analysis.

7.4.3. Degradation potential of the experimental buildings

The monitoring locations were individually analysed for their degradation potential. Despite individual monitoring data of each monitored position, there are majorly two trends of the degradation potentials in the monitoring locations:

In the first trend, the monitoring location of No.6 has moderate risk of degradation potential throughout the monitoring period. The initial RH data of the other monitoring positions (No. 1, No.5, No.6, No.20) were lower than 85% and the RH increased to 85% RH after 1.5 months after the beginning of the monitoring research (Figure 7.36 - Figure 7.39). Straw would have moderate risks of degradation potential within the walls in the monitoring locations after finishing of the straw bale building and spring of next year. Because of the higher monitoring RH at external sensor location in the No.5, the moisture content of straw would be higher around external sensor location the one around inner sensor location. Higher moisture content of straw would lead to higher degradation potential of straw around external sensor locations than inner sensor locations.

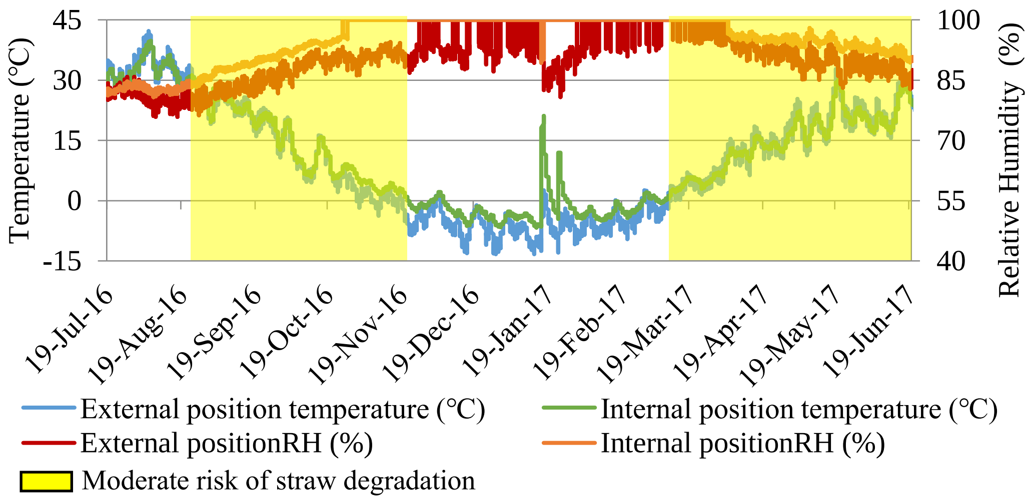


Figure 7.36. Degradation potential of straw of location No.1.

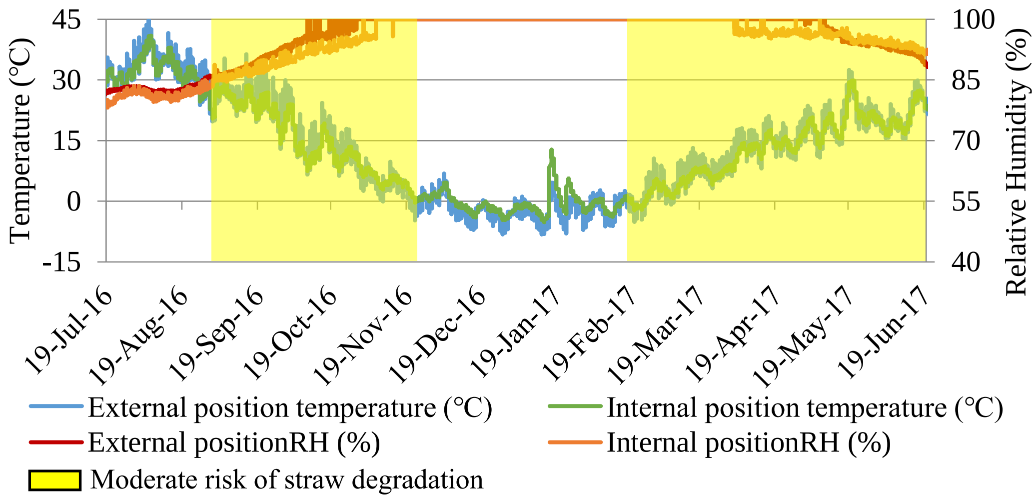


Figure 7.37. Degradation potential of straw of location No.5.

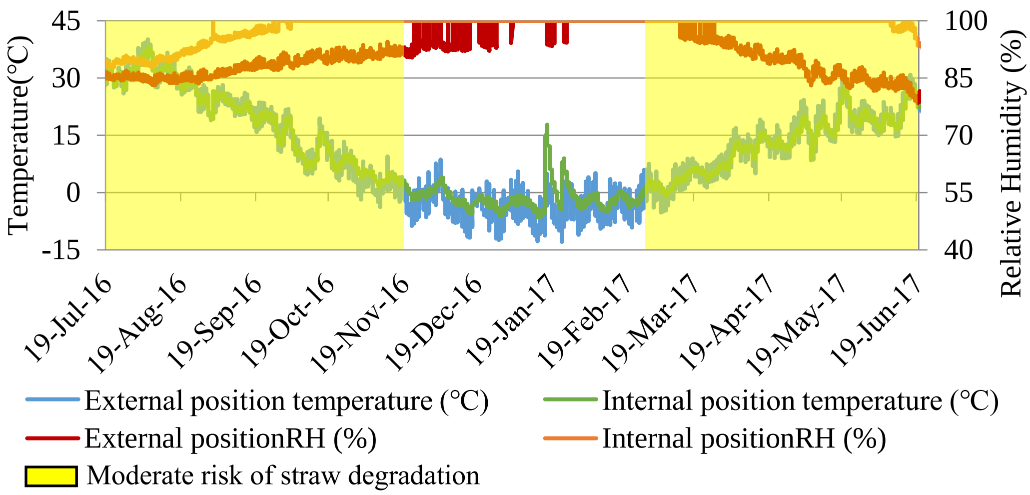


Figure 7.38. Degradation potential of straw of location No.6.

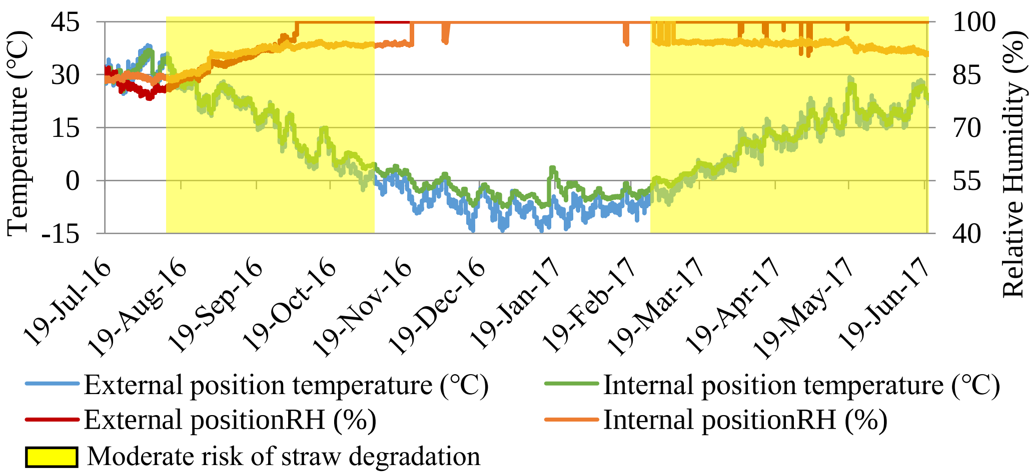


Figure 7.39. Degradation potential of straw of location No.20.

Secondly, most of the monitoring locations have monitored dangerous situation for straw degradation at the beginning of monitoring research and the susceptibilities to degradation are less serious in the following months in the monitoring research (Figure 7.40 – Figure 7.51). The temperatures of all the monitoring positions were over 30℃ at the beginning of the monitoring period and dropped below 30℃ after September 2016. The monitoring RH levels are over 85% in majority of the monitoring positions in the same period of time. The initial RH levels of the monitoring locations were over 85% and then dropped below the 85% after April next year at some monitoring locations (No.4, No.8, No.10 - No.15 and No.19). There is about a 2 months period of time that the monitored hygrothermal environment is over 30℃ and 85% RH in the straw bale walls. For other monitoring locations with the same trend, the degradation potential stayed moderate till the end of the monitoring period.

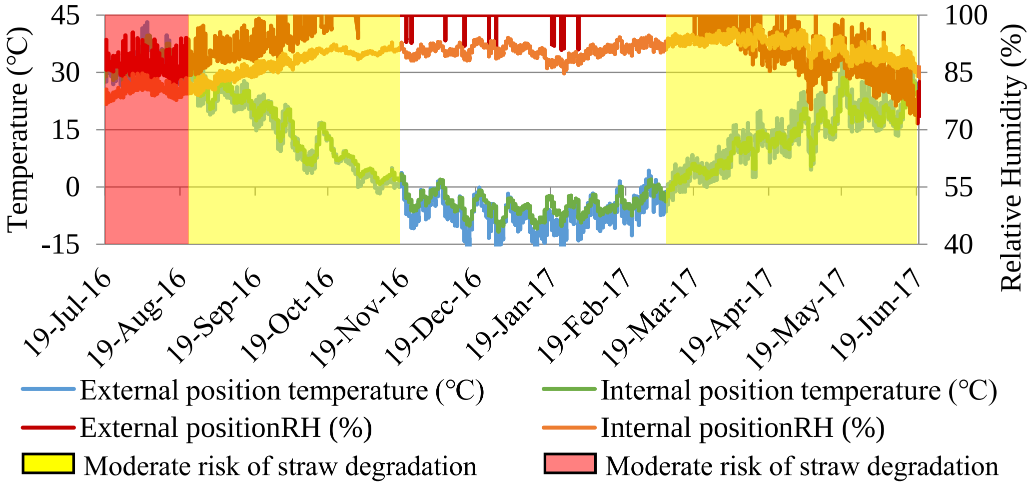


Figure 7.40. Degradation potential of straw of location No.4

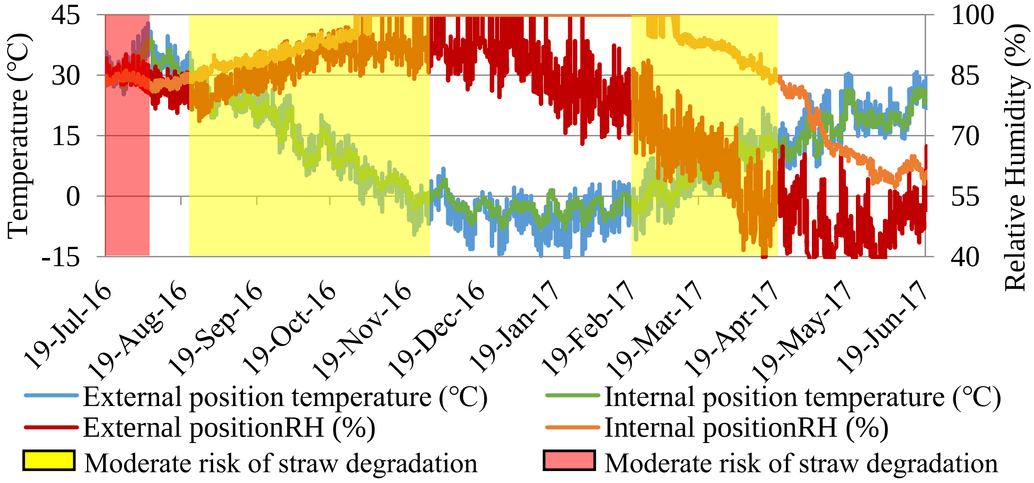


Figure 7.41. Degradation potential of straw of location No.7

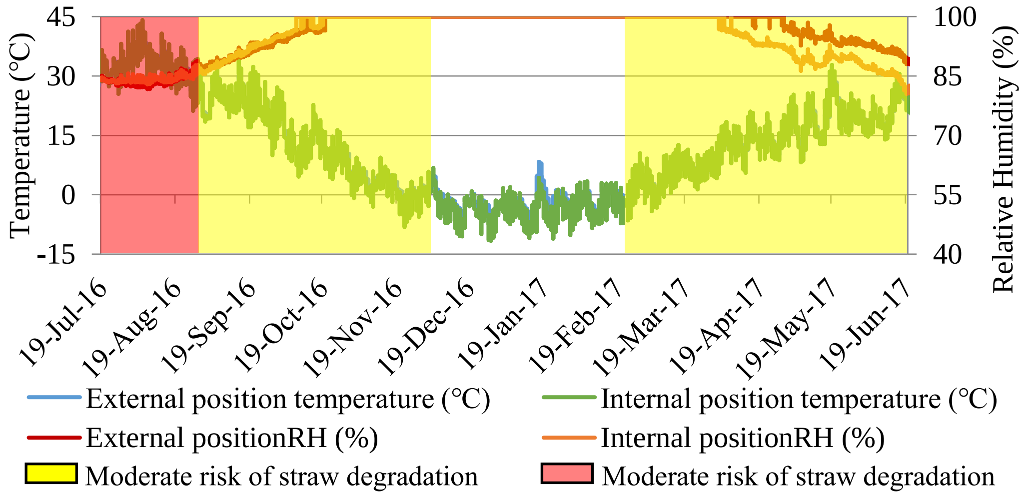


Figure 7.42. Degradation potential of straw of location No.8

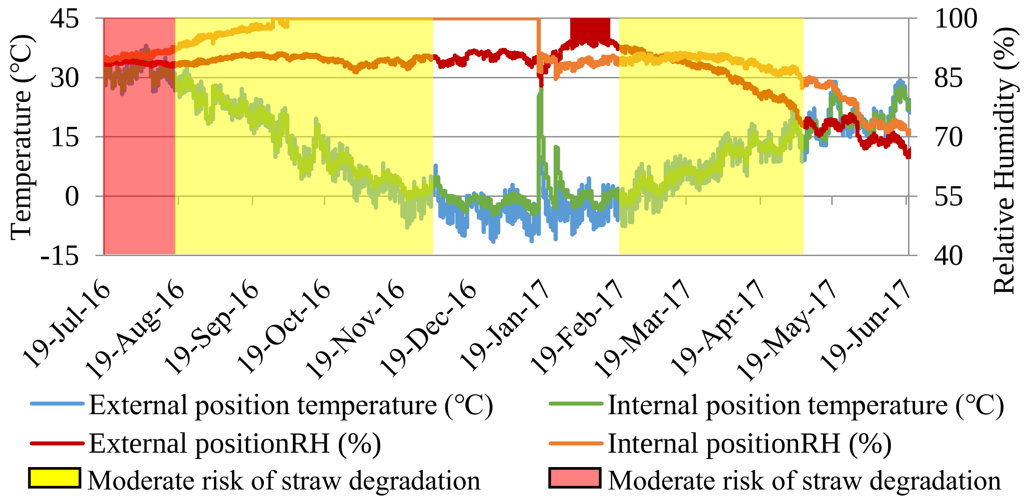


Figure 7.43. Degradation potential of straw of location No.9

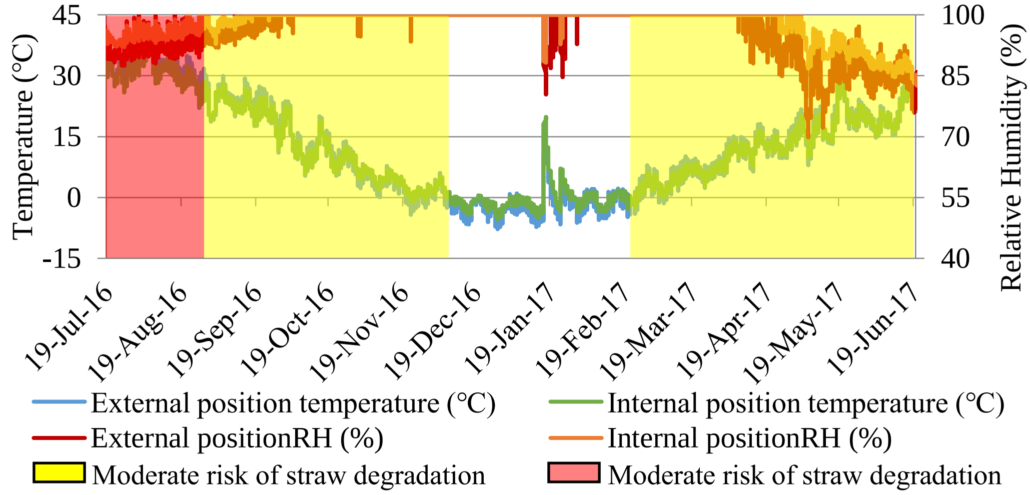


Figure 7.44. Degradation potential of straw of location No.10

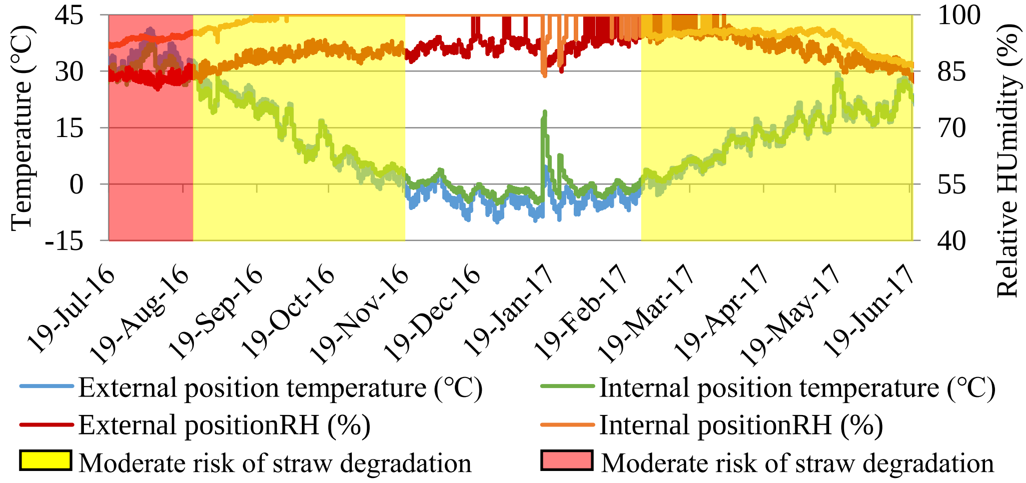


Figure 7.45. Degradation potential of straw of location No.11

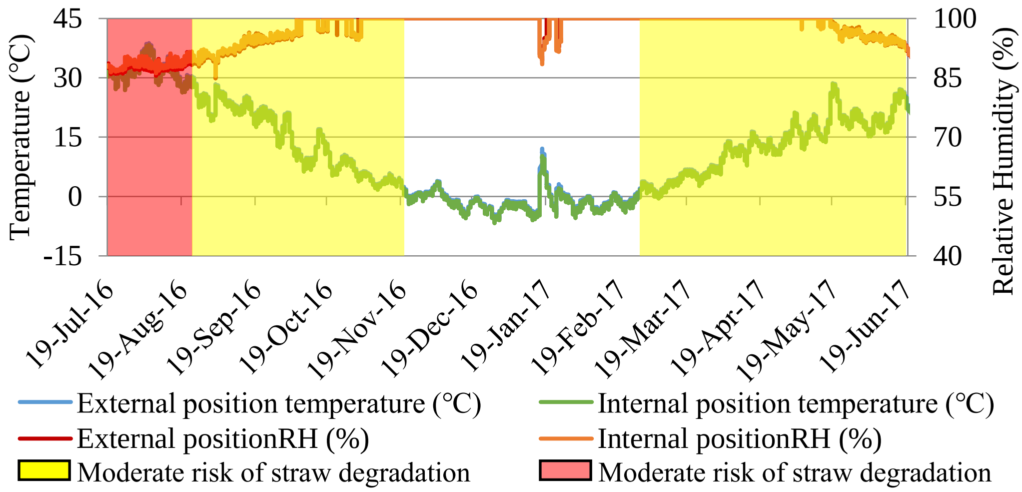


Figure 7.46. Degradation potential of straw of location No.12

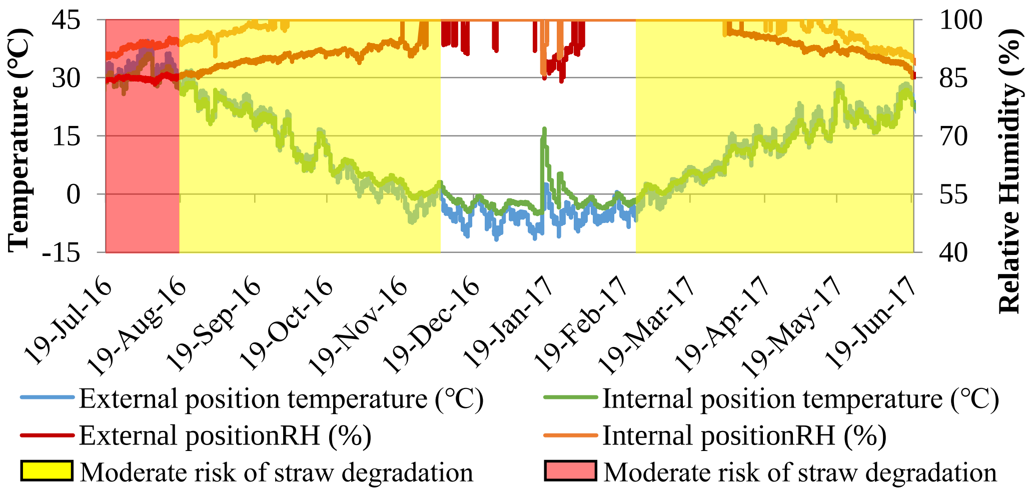


Figure 7.47. Degradation potential of straw of No. 13

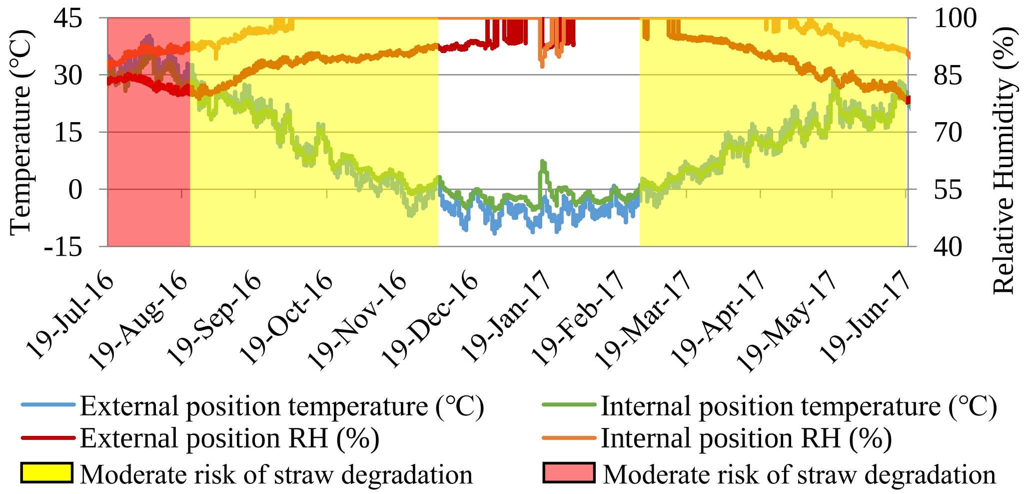


Figure 7.48. Degradation potential of straw of location No.14

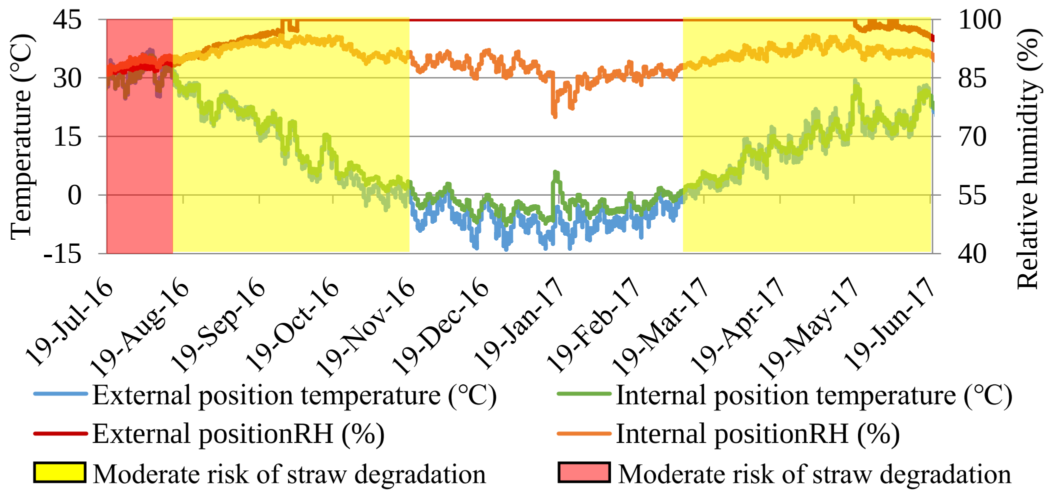


Figure 7.49. Degradation potential of straw of location No.15.

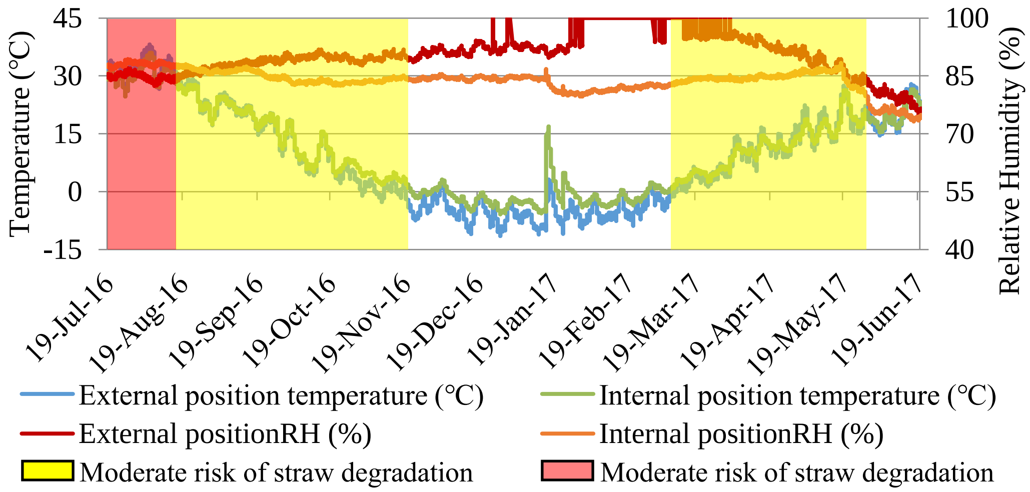


Figure 7.50. Degradation potential of straw of location No.16

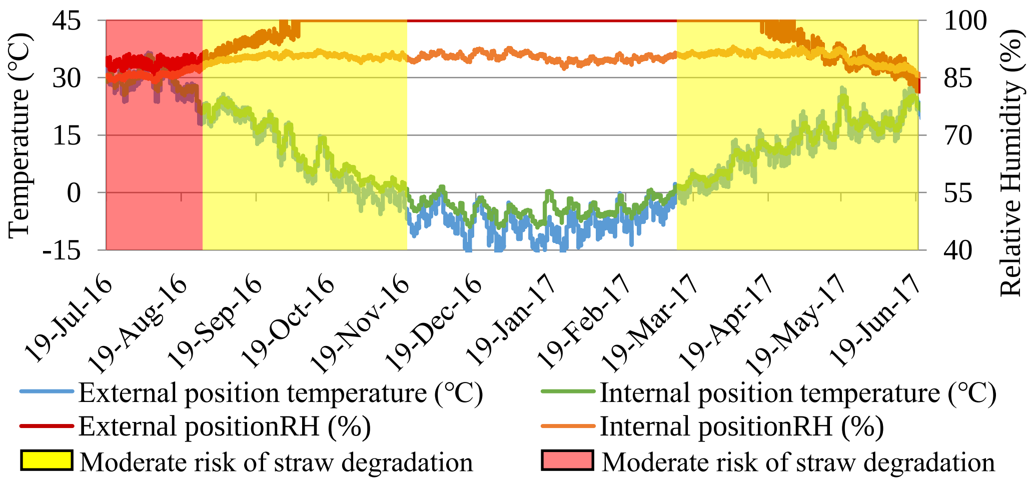


Figure 7.51. Degradation potential of straw of location No.19

The monitoring data of the No.18 are different form the two previous trends (Figure 7.52). The monitoring data of RH levels were lower than 85% RH for the majority of time in the No.18 throughout the whole monitoring research. There are no dangerous situations of straw degradation identified at the No.18 during the monitoring research. The period of time of moderate risks of straw degradation appears in from March 2017 to May 2017. Unlike the low susceptibility to degradation presented in the monitoring data, there is certain degree of degradation identified in the straw bales behind lime render (Figure 7.63). The degradation presented in the monitoring location of No.18 would have close connection to liquefied ice condensation which have been discussed in the previous section.

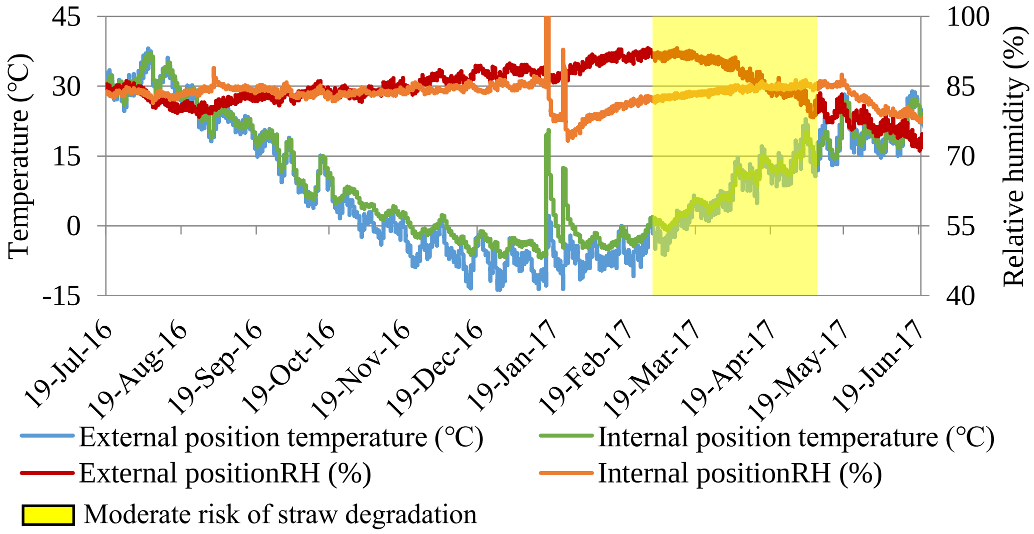


Figure 7.52. Degradation potential of straw of location No.18.

Figure 7.53. Condensation related degradation of straw behind lime render outside monitoring location No.18.

At the end of the monitoring research, The RH levels of the monitoring locations of No.12, No.14, No.15 and No.20 are still greater than 90%RH. As the air temperature would keep increasing greater than 30℃ after the monitoring research, the degradation potentials would become serious in the concessive summer months. The high degradation potential of the monitoring locations map the lower wind intensity of the walling faces. As discussed in the section 7.3, due to slower moisture movement in the sealed-end straw, the walls with laid on-edge bales would be more problematic. Considering the lowest wind intensity of the east walling face, the straw bales inside east gable end would have the most degradation potential in the experimental building.

As discussed in the section 7.3, the high temperature and high humidity environment in the local area in summer limits drying process of straw bale walls and result in trapped moisture inside straw bales. The period of straw bale walls with serious degradation potentials are identified from the start of July 2016 to the end of August 2016. There are few existing research have reported straw degradation risks under such long period of hot and humid environment in the straw bale walls (Bronsema, 2010; Holzhueter and Itonaga, 2014). According to the degradation isopleth (Sedlbauer *et al.*, 2011), serious degradation of straw can be expected in the high temperature and high humidity conditions in summer and therefore this period of time may lead to serious degradation of straw within walls initially after the completion of the experimental straw bale building.

7.4.4. Proposed designs for increasing durability of straw bale buildings in context with climatic features of northern China

To reduce the degradation potential raised by high hygrothermal environment of summer months in northern China, there are two proposed modifications learnt from the experimental building:

a. Application of lime render

Application of lime render can help to increase durability of straw bales inside walling construction which take into account of local climate of northern China. As discussed in the section 3.4.1, the climate of northern China features both short and concentrated raining season from June to August and long and cold winter seasons from November to March. Such climatic condition requires rendering to have high resistance to rain splash and good breathability to prevent moisture build up during winter months. As discussed in section 6.3.2, even though large amount of moisture was introduced into straw bales by the render during construction process, the south facing walls were dried out before the end of the monitoring period. Considering good resistance of lime render against rain splash in practice in the US (Myhrman, 1998) and the UK (Jones, 2009), the lime render is suitable for the straw bale buildings in northern China. However, care should be taken to decrease potential moisture build-up inside straw bale walls during application process of the render layer. As discussed in section 6.1.1, the lime rendering construction was applied and finished within two weeks. Due to short drying process of render layer, following monitoring research identify high initial moisture content of straw bales.

b. Effects of straw orientation inside walling construction

Straw orientation have significant impact on the sorption process of the material as presented in section 4.2. The following monitoring research of the experimental building is also identified the effects of orientation which has been discussed in section 7.3.2. The differences in sorption property of straw orientations have shown notable impact on moisture levels of straw bale walls: as analysed in the section 7.3.2, straw bale walls with laid flat bales have quicker response to humidity changes of the external environment. As discussed in section 7.3.1, diurnal moisture variations of the laid flat straw bales are much greater than the laid on-edge bale walls. Considering effects of seasonal changes, the walls with laid flat straw bales have more moisture intake than the laid on-edge ones which have been discussed in section7.3.2.

With understanding of local climate of the construction site, the effects of stacking method can be used to lower moisture content levels inside straw bale walls. The stacking method of bales should be considered prior to understanding of wind intensities of the construction site. As the straw bales with laid-on-edge stacking method has slower response to humidity changes, the stacking method should not be applied on the walling face with low wind intensity to limit moisture intake of straw bale walls. To increase durability of straw bale walls, the high wind intensity walling face can benefit from the laid-flat bales, as the laid-flat bales have quick response to low air humidity levels and therefore decrease moisture content of straw bale walls. The optimized stacking method of straw bales can decrease moisture intake of walling construction and therefore lower susceptibility to degradation of straw bale buildings. However, because straw inside bales may be randomly orientated in practice, the orientation effects may not as significant as the experimental results in the section 4.2.

7.5. Summary

The prediction models of straw degradation are discussed and analysed which take into account of both the laboratory results and the monitoring data. As the existing isothermal models potentially overestimate moisture content of straw in real situations, the modified model is proposed in context with unsaturated straw in straw bale buildings. The modified sorption isothermal model of straw closely maps the moisture content in the experimental building and therefore the application of the model can produce relative accurate estimation of moisture content of straw in the real situations. In the degradation isopleth model, due to the lime render produce anaerobic and high alkaline environment for straw bale inside walls, the use of the model will lead to overestimation of straw degradation in real situation. However, due to breathability of lime render, the isopleth can predict straw degradation behind rendering layer and therefore the model can be used to estimate degradation of straw at the area between straw bales and rendering constructions.

Analyses of the building investigation of existing straw bale building involve both reviews of the technical drawing of the ADRA project and the results from the building investigation. The technical drawing shows that the design of the straw bale buildings have four disadvantages involving insufficient insulation materials, risks of damp foundation, no bale fixing during construction and selection of rendering material. The identified cracking issues of the straw bale building in Jiamusi has close connection with the improper designs of thermal insulation construction. Based on the inspection of the straw bale buildings in Jiamusi and following computational simulation, the thermal bridging issues are shown to have a close connection with the location of cracking issues on the external surface of render layer. The design of the ADRA project is inadequate with respect to thermal insulation material on the structural elements and detailing design to prevent thermal bridges. This design results in thermal bridging issues on structural frames between straw bales and structural frames. The additional layers of brick work on external surfaces of south walls and north walls, the thermal bridging produces a lower temperature difference between structural elements and insulation on both the external surface and internal surface. On the gable ends, the thermal bridging issue produces a large temperature difference between structural elements and insulation on the surface of the walls. This issue is the likely cause of external surface linear cracking issues around the area between straw bales and structural frames. Taking into account potential human error factors in construction, the thermal bridging can result in frost issues on the internal surface when low temperature occur in winter seasons.

Analyses of the monitoring data of the experimental building show that the humidity levels inside straw bale walls are affected by the wind intensity, the stacking methods of bales and the walling constructions:

Firstly, wind intensities and wind directions have the most significant impact on drying process of straw bale walls and RH distribution within straw bale walls in the three factors. Because of highest wind intensity from south of the experimental building, straw bales have higher RH and vapour pressure inside the south facing walls than the other facing walls after complete of the straw bale buildings in the local climate. The increased RH and vapour presser of the south facing walls decreases to the lowest level than other facing walls at the end of the monitoring research for the same reason. Because there is little wind intensity on north facing walls in the time other than winter, the external RH is higher than internal RH and the highest RH is in the north facing walls at the end of the monitoring research.

Secondly, different stacking methods of straw bales have notable influence on drying period and thermal buffering properties of straw bale walls. The on-edge stacking of bale walls have significantly slower response to air humidity change than the straw bale walls with laid-flat stacking bales. The drying trend data show that the south facing wall with laid flat bales adsorb more moisture than the laid on-edge one and reach complete dried condition 3 months earlier than the south facing wall with laid on-edge wall. The diurnal vapour pressure data of the laid flat walls also shown greater daily gradient of the vapour pressure change inside the walls than the laid on-edge walls. The walls with laid-on-edge bales feature notable increased thermal buffering properties than the laid flat bales.

Thirdly, the walling construction also have notable impact on moisture content of straw inside walling constructions. Due to more complex walling construction around window sill, construction quality issues may be easier found in the construction. As a result, straw in the locations may have greater susceptibility to degradation than the one inside a straight wall.

By applying the modified prediction models, the susceptibility to degradation of straw can be assessed through monitoring results. Straw bales inside the experimental building experienced environment of high degradation risks for after initial completion of the experimental building in summer months during the monitoring period. The high risk of degradation environment was continuously lower in the following winter months and the spring next year. Concluding from the results of the experimental building, for further construction of straw bale buildings, the susceptibility to degradation can be reduced by applying lime render and optimized stacking method of straw bales which takes into account of wind direction and wind intensity of the building site.

8. Conclusion and recommendations

8.1. Conclusions

The main aim of this study was to propose appropriate building designs for straw bale buildings which optimise their durability given the known sensitivity to degradation of existing straw bale buildings in northern China. The design developed takes account of straw variety, issues with existing details, and observed in-situ performance. This aim has been successfully fulfilled, though further research is recommended for the widespread adoption of straw bale construction in China.

8.1.1. Durability of straw

There is limited understanding of the durability mechanisms of straw and how the resulting durability properties depend on the physical characteristics of the straw. The first objective addressed this;

- *The first objective is to understand the durability of the straw as a building material. The objective involves achieving both an understanding of moisture adsorption process of rice straw and an evaluation of the susceptibility to degradation of both wheat straw and rice straw in high humidity and high temperature conditions. Whereas wheat straw has been heavily researched, there is little published research on rice straw. For this reason, this study places particular emphasis on rice straw and on the characterisation of the microscopic structure and moisture adsorption properties of both rice straw and wheat straw. Having obtained an understanding of the two straw species, a modified isothermal model of straw will be proposed in the context of the actual environmental conditions that straw bale buildings are subjected to in northern China;*

This objective was satisfied through an experimental study of the physical characteristics and resulting isothermal sorption properties of individual straw varieties and a small scale wall build up.

The microscopic inspection of rice straw shows that the waxy surface of rice straw has spiky nodes present which are not identified on the surface of wheat straw which are likely to be responsible for the higher resistance to compressive loads reported in rice straw bales. The cross section of rice straw is also notably distinguished from the one of wheat straw, with the end grain pore size of rice straw, notably smaller than that of wheat straw. The pore sizes of rice straw are under 10 μm whereas the pore sizes of wheat straw are vary from 10-50 μm. Although the wheat straw and rice straw both incorporate vascular bundles containing phloem and xylem cells, the size of these bundles in wheat straw is significantly larger.

Despite the differences in the microscopic structure of wheat straw and rice straw, the moisture adsorption of the two species are broadly similar. Both the two straw species demonstrate similar adsorption isotherms and show a similar period of time for the adsorption process to reach particular levels of moisture content. However, the pathways of moisture migration into the straw have a notable impact on the adsorption process of both straw species. The straw tends to have quicker adsorption process through the end grain of the straw than through the waxy surface of straw. However, the effects of orientation on straw adsorption are less significant when the straw is exposed to the surrounding humidity for a sufficient length of time.

Based on the results of the moisture adsorption research of the two straw species, a modified isothermal model is proposed which reflects realistic environmental conditions. As the existing isothermal models are based on the saturation status of straw which would not often be achieved in the climatic conditions in northern China, the modified isothermal model is based on unsaturated experimental results from the DVS equipment. Suitability of the model is verified through a comparison of monitored results and calculated results of the moisture content of straw bales in the experimental building. The modified model can broadly predict moisture content of straw during adsorption process; whereas existing isothermal models generate more accurate prediction of moisture content of straw during desorption process in the climatic condition in northern China.

A major challenge for the isothermal model is the different conditions between diurnal situations and the experimental set-up. The adsorption isothermal model for predicting the moisture content assumes a steady diurnal variation, whereas in reality diurnal variations are irregular and can vary quite rapidly. Existing adsorption isothermal models are based on saturated adsorption of straw which is not based on rapid random variations of relative humidity and therefore the critical RH for straw degradation is unlikely to be achieved as rapidly as the model would predict due to the natural lag in adsorption kinetics.

The susceptibility to degradation of straw within a typical construction has been investigated through 12 weeks exposure of straw bale walling section in the climate chamber with 95% RH and 35 °C. The results show that with the addition of lime plaster, the straw stayed unchanged compared to its initial status. This provides reassurance that the susceptibility to degradation of either rice straw or wheat straw would not be significant under the hot and humid summer conditions to which straw bale walls in northern China would be exposed.

According to the hygrothermal monitoring data, the RH/T conditions within straw bale walls do not change significantly on daily basis. The modified isothermal model is designed to accommodate the real conditions as observed in northern China. The modified isothermal model in this research would be closer to real situations than existing isothermal models in predicting moisture content of straw. In further research, the modified isotherm model will benefit from calibrations using moisture meters inside straw bale walls in real situations.

8.1.2. Review of existing buildings

Straw bale construction was introduced to Northern China 20 years before this thesis was written, however, it has not been widely adopted. The existing buildings have been evaluated with respect to their performance. The second objective addressed this;

- *This research will provide an understanding of the performance and condition of existing straw bale buildings in northern China. It has been almost 20 years since the initial introduction of straw bale buildings by ADRA in 1998. There is much research focusing on the benefits of straw bale buildings and on the feasibility of implementing straw bale building based on the ADRA project in northern China. However, there is little research evaluating the buildings in terms of buildability and possible performance and durability issues. This research will investigate both the straw bale buildings from the ADRA project and other straw bale buildings where innovative designs were informed by ADRA project. The research will* *involve site visits to straw bale buildings, evaluation of construction methods, description and analysis of defects found in the existing buildings and recording the opinions of straw bale buildings by local residents;*

The status of existing straw bale buildings in northern China has been examined through both site visits to the buildings and analysis of the buildings regarding identified issues, building method and feedback from local residents. Two major projects have been included in this thesis. As the majority of straw bale buildings in northern China are a result of the ADRA project, the thesis considered these buildings in particular.

A site visit of the ADRA project examined 34 straw bale buildings in the ADRA project in Jiamusi. There were 7 buildings in occupation at the time of the completion of this thesis. The majority of the buildings have been either abandoned or demolished within 20 years of their construction. The existing buildings have notable cracking issues on the surface of the render layer. A visual check in 2015 of the straw status of a recently abandoned building identifies notable straw degradation.

Analysis of the detailing designs of the straw bale buildings show that the designs of the buildings have a notable defect involving inappropriate designs of the thermal insulation layer. Computational simulation of the issues identified that the design will lead to low surface temperature of the inner corner of the buildings, likely due to errors when installing the thermal insulation layer. This situation can lead to frost issues when external temperatures are extremely low in winter. As clear thermal bridging issues are identified in the computational simulation results, different thermal expansion ratios of external rendering layer is one possible explanation of the cracking issues identified in the site visit.

The feedback from local residents show a great prejudice against straw bale buildings in the ADRA project. Considering the issues identified in the site visit of the buildings, local people do not have positive views of straw bale buildings. However, according to the feedback from local residents, the identified issues may have been due to a lack of maintenance of the buildings. One notable fact for the reasons behind the abandoned straw bale building are that people are moving home from the local area to be near cities and mega cities. As a result, it is likely that the remaining inhabited straw bale buildings will be abandoned within a few years after the competition of this thesis.

8.1.3. In-situ durability assessment

While the durability performance was investigated in the laboratory for individual straw and idealised wall sections, understanding in situ performance was key to the overarching aim. As identified from the existing straw bale buildings, various construction details can lead to accelerated degradation of the construction, which needs to be addressed and the improvements validated;

- *The third objective is to evaluate the durability of straw bales in straw bale buildings in the climatic conditions in northern China. An experimental building in the area will be constructed to allow the evaluation of the durability of straw bale buildings when exposed to the climatic conditions of northern China. Long-term monitoring research of the straw bale walls of the experimental building will be conducted and the results of the monitoring research will be analysed by applying existing models for predicting straw degradation. The suitability of the models will be examined through a forensic investigation of the experimental building at the end of the monitoring research period.*

Construction of the experimental straw bale building featured modifications to the existing construction detailing in the ADRA project. The experimental straw bale building introduced a pinning system, toe-up base plate and lime render. For research purpose of comparing different stacking methods of straw bales, both laid flat straw bale walls and laid on-edge straw bale walls are applied in the straw bale building. Construction processes of the straw bale building identified that the combination of the timber frame and straw bales are easy to work with for the local builders. However, due to the unusually early rain season during the construction process of the experimental building, both serious bale damage and delayed building schedule were encountered in the construction of the experimental building.

The monitoring results show that there was a significantly long drying process for the rendering in the environmental conditions in northern China. Apart from south facing walls, none of the other walling faces did achieved complete drying of the render by the end of the monitoring period. The monitoring results show that the south facing wall with laid-flat bales have shorter drying period than the south facing wall with laid on edge bales. Due to the long drying process of the lime render, straw inside straw bale walls would have potential of condensation occurring in the following spring after the completion of straw bale buildings due to the local climate conditions. The results of the monitoring research also validates the benefits realised through the detailing changes made to the walling construction. More complex walling details such as around the windows will lead to a higher expectation of failure especially immediately below window sills, requiring even greater attention to quality in these areas.

The RH/T sensors used in the monitoring research were unreliable in producing consistently accurate readings during the winter. 100% RH was recorded during the monitoring research in winter months. However, instant change of RH readings between 94%RH to 100%RH during winter months indicate that the electronic RH/T sensors were unable to produce accurate RH data in high humidity environment in the straw bale walls, as occurred in the first winter of the monitoring process. Knowing the hygrothermal environment in the straw bale walls is crucial to being able to predict moisture movement between straw bale walls and the external atmosphere. The use of straw bale moisture content probes might prove to be a better alternative to electronic RH/T sensors. However, such probes would need to be calibrated and validated for use in low temperature environments, as experienced in northern China.

Both serious and moderate susceptibility to degradation of the experimental building were identified. For the majority of monitoring locations, the susceptibility to degradation, whilst initially serious, reduced to moderate by the end of the monitoring period. However, there was no notable degradation identified on-site as predicted by the laboratory investigation.

8.2. Recommendations

This thesis presents the development and experimental investigation of the durability of straw bale construction within China. Further research is recommended to achieve widespread mainstream adoption of straw bale construction in China.

8.2.1. Straw Bales

This research has identified that the orientation of straw has a notable impact on moisture adsorption of straw and thus the orientation of straw bales has an impact on moisture migration through straw bale walls. Further research should focus on an examination of breathability of straw bale walls in relation to straw orientation. Since straw may be randomly orientated inside straw bales, further development using straw in different forms rather than straw bales may also be of the interest for further research.

This research has shown that the rice straw can be successfully used in the straw bale buildings in northern China. The experimental straw bale building uses rice straw in construction of straw bale walls in this research. The use of rice straw would be recommended in further construction of straw bale buildings in northern China. There are three significant advantages for using rice straw in straw bale constructions:

1. Availability of the raw material. The availability of rice straw is guaranteed by the large amount of rice farming in northeast China;

2. Based on building construction process of the straw bale building in this thesis, rice straw is a reliable building material for straw bale constructions;

3. The experimental work on rice straw in this research found out that the rice straw has low susceptibility to degradation in the climatic conditions of northern China.

8.2.2. Monitoring

The monitoring of the experimental building is continuing beyond the 11 months of data collected and presented in this thesis. Full monitoring data will be achieved in August 2018 resulting in 23 months of monitoring data of the experimental building. Further research on the experimental building will involve final demolishment of the building and examination of straw conditions and validation of the building designs.

8.2.3. Straw bale buildings

Concluding from the building process of the experimental building described in the section of 6.2, one significant drawback of traditional onsite construction of straw bale buildings is the potential for damage to the bales through exposure to rainfall. During the construction process of the experimental straw bale building in this research, around half of the straw bales were damaged by unexpected rainfall. Onsite construction of straw bale walls would be even more susceptible to damage caused by rainy weather in larger building projects. Other than the raining issues, fire risk management for straw bale constructions would pose greater challenges for large scale of building developments. Prefabricated Straw Bale Construction (PSBC) would be more appropriate for building projects with a high requirement of on-site management of fire risks. Prefabrication processes of the straw bale walls would also have advantages in minimising exposure to adverse weather conditions and assuring quality control of the walling panels. The properties of PSBC would suitable for the building projects with tight construction schedules and a high requirement for uniform quality of building materials.

It is recommended that lime render should be used in all future straw bale buildings in northern China based on the strong relationship between the use of lime render and improved straw durability, shown in the section of 7.2. However, due to high initial moisture intake of straw bales which was identified in the experimental building in the Chapter 6, care should be taken to minimise the amount of moisture by extending the time taken to apply the lime render.

As the thermal properties and moisture buffering capacities of straw bale buildings are significantly different from other building types, the indoor environments of straw bale buildings would be notably different from the existing building types in northern China. An understanding of the impact of straw bale buildings on the indoor hygrothermal environment of the buildings in climatic conditions of northern China would be particularly helpful to justification of use of this building type. Secondly, due to there being little application of rice straw in straw bale buildings, there is a poor understanding of the embodied carbon of rice straw. As low carbon emission of straw bale construction is a key advantage of the building type, an understanding of the carbon emissions associated with rice straw would help to promote the application of the material in straw bale construction.

8.3. Concluding comments

This thesis modified the design of existing straw bale constructions and builds up fundamental research on application of straw bale buildings in the northern China. The results of this thesis are critical for further development of straw bale buildings in northern China and the rest of the world.

This thesis identifies potential risks for using straw bale building in northern China and proposes appropriate detailing for the construction of straw bale buildings which will be subjected to the wet and cold climatic conditions of that area. The main benefits for bringing this method of construction to northern China are to reduce the use of conventional building materials by substituting rice straw, which is an agricultural bi-product; and to reduce the environmental impact caused by its disposal, which is currently by being burned, causing significant pollution and carbon emissions. The high thermal insulation properties of this approach make it particularly effective in this region given its harsh climate. In addition this approach can help deliver the Chinese government's energy reduction target through its low environmental impact. This will contribute to the sustainable growth of China, whist minimising the operational impact on the environment and the carbon footprint of buildings.

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